THE UNIVERSITY OF ALBERTA

HYDRAULIC TRANSPORT OF FLUIDIZED SOLIDS IN OPEN-CHANNEL FLOW

by

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A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Hydraulic Transport of Fluidized Solids in Open-Channel Flow" submitted by Ralph William Ansley in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

ABSTRACT

This thesis summarizes an investigation of open-channel hydraulic transport of fluidized solids. Data are reported for an experimental study of both pipeline and flume transport of sand-water and fines-sand-water slurries.

The experimental apparatus is described in detail. The experimental techniques are outlined and an analysis of accuracy of results is included.

The accepted theories of pipeline transport of fluidized solids are examined as background for an analysis of open-channel transport.

A correlation for critical deposit velocity in flumes is developed by dimensional analysis and is confirmed experimentally for sand-water slurries. The correlation is shown to apply to pipeline transport of sand-water slurries.

* * * *

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D = Measured internal pipe diameter in feet.

D_1 = 0.0874 ft. for 1-inch Schedule 40 steel pipeline.

D_2 = 0.0874 ft. for 1-inch aluminum pipeline.

D_3 = 0.1715 ft. for 2-inch Schedule 40 steel pipeline.

D_4 = 0.1715 ft. for 2-inch aluminum pipeline.

b = Mean breadth of flume = 0.50 ft.

y = Mean depth in flume in ft.

R = Hydraulic radius in ft.

γ_w = Specific weight of water = 62.4 lbs./ft.^{3}

γ_s = Specific weight of sand = 165.4 lbs./ft.^{3}

γ_f = Specific weight of fines = 169.1 lbs./ft.^{3}

γ_{sl} = Specific weight of sludge solids = 169.1 lbs./ft.^{3}

G_s = Specific gravity of sand = 2.65

G_f = Specific gravity of fines = 2.71

G_{sl} = Specific gravity of sludge solids = 2.71

ρ_w = Mass density of water = 1.94 slugs/ft.^{3}

ρ_s = Mass density of sand = 5.14 slugs/ft.^{3}

ρ_f = Mass density of fines = 5.26 slugs/ft.^{3}

ρ_{sl} = Mass density of sludge solids = 5.26 slugs/ft.^{3}

C_s = Concentration of sand by volume.

C_f = Concentration of fines by volume.

C_{sl} = Concentration of sludge by volume.

g = Acceleration due to gravity at Edmonton = 32.2 ft./sec.^{2}

Q = Discharge in ft.^{3}/sec.

V = Mean Velocity in ft./sec.

ν = Kinematic Viscosity in ft.^{2}/sec.

ν_a = Apparent Kinematic Viscosity in ft.^{2}/sec.

R_e = Reynolds Number in terms of water viscosity.

BR_e = Bingham-Reynolds Number in terms of slurry apparent viscosity.

F_r = Froude Number.

i_w = Hydraulic Gradient of water.

i = Hydraulic Gradient of mixture measured in ft. of water per ft. of pipe.

Φ = Non-dimensional parameter for hydraulic gradient $= \frac{i - i_w}{C_s \, i_w}$

f = Friction factor defined by Darcy-Weisbach equation.

W = Terminal settling velocity of a solid particle in water in ft./sec.

C_x = Drag coefficient.

ψ = Sphericity Factor.

C_{x^1} = Apparent drag coefficient.

V_c = Critical deposit velocity.

CHAPTER I

INTRODUCTION

1.1 Hydraulic Transport of Fluidized Solids:

Materials in the solid state may be conveyed by dispersing the particles in a moving stream of a continuous fluid phase. This has been done successfully over a wide range of different materials such as gilsonite, coal, wheat, golf-balls and quartz, in fluids both in the liquid and gaseous state. For compressible fluids, the transport has always been in closed-conduit flow; whereas in the case of incompressible fluids the transport has been carried out both in open-channel and closed-conduit flows. In most cases, the solids transported have had a specific gravity greater than that of the fluid phase. The hydraulic behaviour of the solids-fluid mixture is dependent on the concentration of solids, the specific gravity of the solid material, the particle size and shape of the solids and the velocity and consistency of the transporting fluid.

Hydraulic transport of solids has become widely applied during this century, due to the rapid development of such solids-handling industries as mining, ore concentrating, dredging and coal transport. However, for the most part the literature associated with the hydraulic transport of the solids has been quite limited and of a practical rather

than a theoretical nature. Most individual operators have discovered their optimum conditions experimentally and in most cases collected no data or, if collected, these were not reported in the literature.

1.2 Current Technology:

The recent commercial development of fluidized solids transport has stimulated considerable interest in the technical aspects of the technique. A detailed review of the literature would be somewhat redundant in that there are several excellent, up-to-date, historical reviews of the literature (Chamberlain et al, 1960; Babcock, 1962; Thomas, 1962). A comprehensive catalogue of available data has been prepared by Chamberlain et al (1960). Hughmark (1961) listed several data sources in the field of chemical engineering. Condolios and Chapus (1963) have given a current discussion of the latest theoretical approaches.

Unfortunately, the work to date has been carried out generally in four different categories of fluidized solids transport, with no concerted effort towards a unified approach. This has resulted in several classification systems being put forth (Govier and Charles, 1961; Newitt et al, 1955). The four broad categories are based on closed-conduit flow, open-channel flow, continuous-phase homogeneous slurries and heterogeneous slurries exhibiting a density gradient.

Some workers have carried out analyses of data collected from commercial operations and augmented them with laboratory test data. From this standpoint, there is considerable literature available

on the subject of closed-conduit transport of solids such as sand, gravel and coal as a solids-water slurry. These types of slurries have been classified as heterogeneous mixtures and to date the published results are empirical equations based on data which apply only to the particular material which was tested. There are several correlations which purport to cover a wide range of solids with varying particle sizes in different-size pipes. In the case of the so-called homogeneous mixtures, there is considerably more literature available discussing a theoretical approach. These mixtures generally exhibit non-Newtonian behaviour at appreciable concentrations of solids. A rheological investigation can be carried out for design in the laminar region. Newitt (1955) has advanced a hypothesis describing fully turbulent flow.

In the case of open-channel flow, the literature is somewhat confusing. During the recent rapid development of mobile boundary hydraulics, there has been a good deal of literature on sediment transport in rivers, canals and flumes, but always in very low concentrations. For the most part in these investigations, the sediment transport was a side issue and has been investigated primarily as to its effects on the hydraulics of the channel in which it occurs. On the practical side, there are many installations (carrying high-solids concentrations in flumes) that have been in operation for more than twenty years. Here, the procedure has been to modify the installation until it worked for the particular conditions set by the streams involved. Unfortunately, to date, neither the classifiers nor theoreticians have directed their attention towards this type of solids

transport. There are no published design criteria for transport of either high-concentration heterogeneous mixtures or homogeneous mixtures in open-channel flow.

On occasion, both homogeneous and heterogeneous mixtures have been available concurrently. Usually, these streams have been handled separately in commercial operations, but in some instances they have been blended and transported either in pipeline or open-channel flow. In the case of the pipeline transport, the literature contains data only on the particular mixture studied. However, Newitt (1955) has put forth a theoretical correlation. The author is unaware of published research results on open-channel transport of these mixtures at high concentrations. The literature, however, is very extensive on mobile boundary hydraulics with bed load (Blench, 1957).

1.3 Purpose and Scope of Investigations:

This thesis deals with a commercially-sponsored research program currently being carried out in the Civil Engineering Department of the University of Alberta and summarizes the data collected and conclusions reached during the first phase of the program.

The investigation reported herein has been directed toward studying the bed formations associated with open-channel transport of fluidized solids. The three basic objectives were to describe the physical phenomena, find an equation of condition for the formation of a bed and to study the effect of fines on the first two.

In a proposed commercial operation, the sponsor contemplates a larger continuous fluidized solids system than ever before operated. In general, the proposed commercial operation consists of the conveyance and disposal of two streams which are 7,300 tons per hour of + 325 mesh solids and 1,630 tons per hour of - 325 mesh solids. Since both these streams of solids appear in a solids-water slurry, it would at first glance appear more attractive to convey them hydraulically than to unwater them for subsequent dry transportation. Extremely high maintenance costs are usually associated with pipeline transport of fluidized solids when the solids are in the sand size range or larger. The rule-of-thumb used in the industry suggests that the wear on pipes is roughly proportional to the third power of the velocity. (Bergeron [1962] states that it exceeds this value). Flume transport has more attractive maintenance costs but presents serious design and operational difficulties, such as high water requirements and inability to handle the solids feed rate surges. The sponsor is primarily interested in applied research to facilitate the design of the commercial installation.

Although the test work was confined to two particular solids dispersed in water with the object of gaining specific design data, the research program was directed towards an investigation of the fundamental characteristics of hydraulic transport of fluidized solids. The study was initiated during the summer of 1959 and has been carried on continuously up to the present. Basically, the approach has been to conduct literature research, inspections of commercial operations and laboratory testing. The author has been fortunate in that the sponsor has been most generous in supplying both funds and technical personnel to aid in the program.

During 1959 and 1960, an orientation literature review was undertaken, which was summarized in a brief report including a bibliography.

During the period 1959 to 1961 inclusive, the author had the opportunity to travel extensively, visiting commercial applications of hydraulic transport of fluidized solids, both in North and South America. Discussions with the operators proved invaluable in setting up the tentative objectives of a laboratory testing program. These inspections also provided the author with a first-hand knowledge of the operational difficulties associated with the prototype applications. Wherever possible, the author collected on-site data to augment those data subsequently developed in the laboratory testing.

The sponsors had carried out considerable research on a bench-scale process unit at Lake Charles, Louisiana, during 1958 and 1959. The author observed a series of these runs during July 1959 to gain some background information for the fluidized solids handling requirements. A large-scale pilot plant was subsequently built during 1959 and operated during 1960 at Mildred Lake, Alberta. The author was very active in the design and initial operation of this plant, which demonstrated the design difficulties which could be anticipated in a commercial operation. Since many facets of the proposed commercial plant required considerable detailed research, pilot testing of the hydraulic transport seemed timely and desirable. A testing unit was build in the Hydraulics Laboratory at the University of Alberta, using funds supplied by the sponsor.

A cursory literature review had shown that there were considerable data published on the handling of sand-water slurries, particularly in the approximate size range of the sand which the sponsor contemplated handling. Since the literature contained published empirical correlations for predicting pressure drop when conveying sand-water mixtures in pipelines, it seemed reasonable to check the characteristics of the sand-water slurry against the published data and to use this stream as the initial feedstock for the testing unit. Pipeline tests were carried out before initiating similar tests in the flume, on the premise that the known closed-conduit characteristics of the slurry would be useful in interpreting the open-channel flow experimental data.

The first phase of the testing program was, therefore, to carry out pressure drop observations in the 1" and 2" pipelines for a range of slurries from zero per cent to 35% by volume sand, over as wide as possible a range of velocities. Slurry is defined herein as mixture of solids and liquid with a continuous liquid phase. In particular, emphasis was placed on determining that velocity at which the sand began to deposit on the bottom of the pipe. This velocity is noted herein as the "critical deposit velocity." This phase of the investigation was standard, in that it would provide empirical data which would ultimately be used in the design of the proposed commercial operation. The published work on pipeline transport of sand slurries (Durand, 1952) includes empirical design equations for pipe sizes from 1 inch up to 28 inches in diameter. It was hoped that the experimental data could be correlated to the Durand equations

for small pipe sizes and thus establish a design basis for scale-up to a large-size prototype installation. The determination of critical deposit velocity for a given system has been shown to be extremely important from an operational viewpoint (Fraser, 1960). The aim was to find some method of predicting the critical deposit velocity for the prototype system without conducting the full-scale testing described by Fraser.

There is a good deal of literature available on fines-water slurries, but unfortunately most of the work has been associated with small pipeline transport, particularly in the laminar range. The emphasis has been on laminar investigations since at relatively high concentrations, fines-water slurries exhibit non-Newtonian behaviour. These mixtures are generally considered homogeneous and there are no data in the literature dealing with the critical deposit velocity as defined herein, for such mixtures. At present there are no data available on open-channel transport of these fines-water slurries and, again, it seemed advantageous to conduct a series of tests in the pipelines before proceeding with the open-channel flow investigations. An independent rheological investigation was carried out on the fines-water slurries in the hope that the rheological properties could be used to explain any anomalous behaviour observed in the tests.

During discussions with operators of fluidized solids systems, the author was advised that the coarse-solids carrying capacity of a system was generally increased substantially when fines were introduced into the stream. In particular, it had been noted that for a

flume at a given slope a greater amount of tailings could be carried without deposition of the solids in the form of a bed on the flume, if fines were added. This phenomenon has also been used by dredging operators to successfully unplug lines which had filled with sand or gravel. The literature search revealed very limited information on the subject of fines-sand-water slurries. The testing program was directed toward an investigation of the effect of fines on the sand-carrying capacity and critical deposit velocity for both the pipeline and flume transport.

The testing program was originally designed to carry out the investigation in four phases. The first phase was to calibrate the system, using clear water in both the pipelines and the flume. These tests were re-run after completion of all the other three phases, for re-calibration purposes. The second phase was to pump and flume sand-water mixtures over a range of concentrations from zero to 35% by volume. The third phase of the program was to pump and flume fines-water mixtures over a range from zero to 40% by volume. The fourth and final phase of the program was to carry out both pumping and fluming tests on a series of fines-sand-water slurries, trying concentrations of both the fines and the sand to as large a degree as possible.

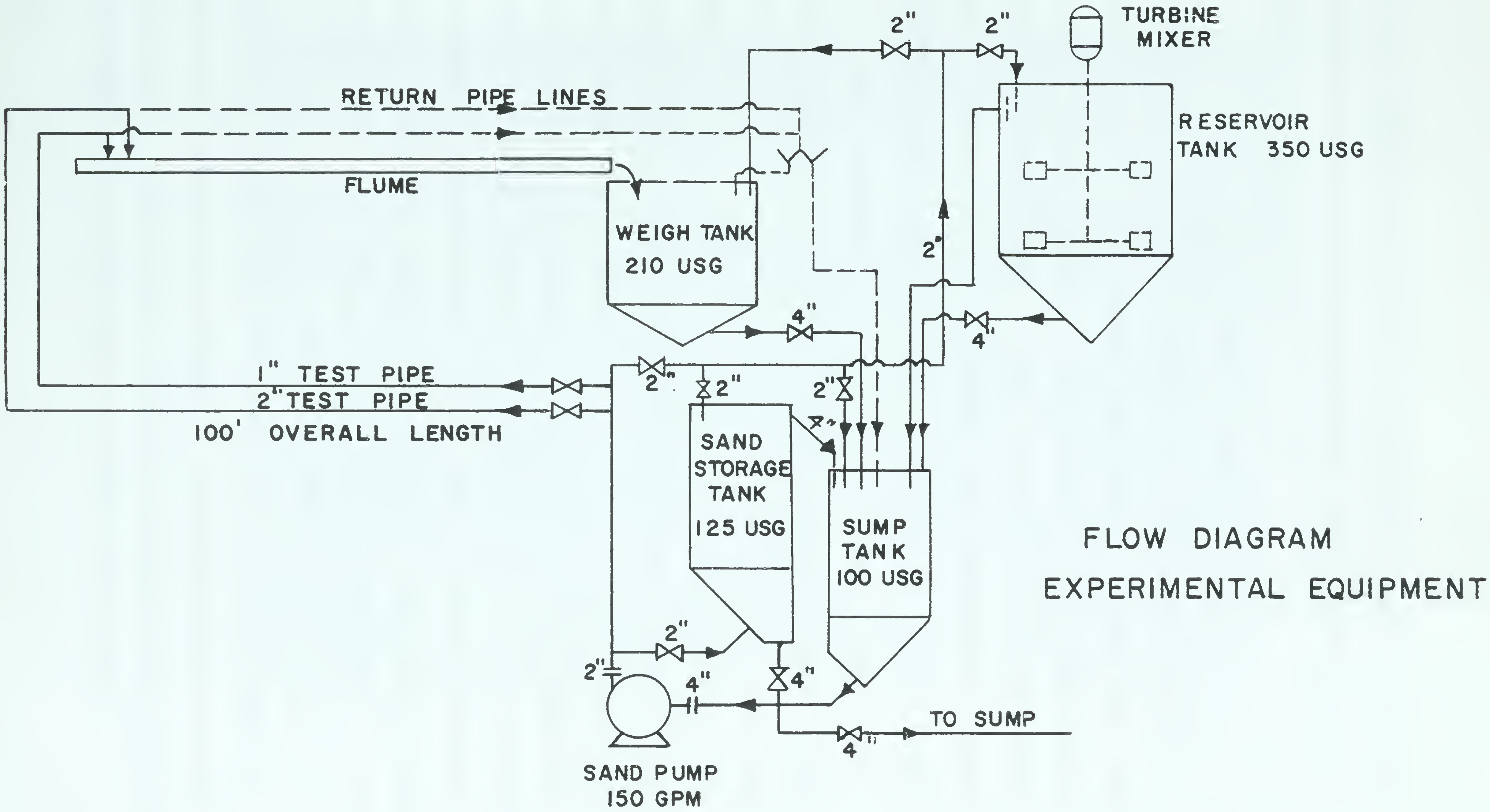
CHAPTER II

EXPERIMENTAL PROGRAM

2.1 Flow Sheet:

A line diagram of the experimental apparatus can be seen in FIG. II-1, entitled "Flow Diagram - Experimental Equipment." The basic concept of this equipment is to provide a recirculating system capable of handling dense slurries of solids in water through both pipes and flumes without dissociation of the slurry at any point in the system. The flow sheet was designed at the beginning of the experimental program and has only undergone minor modifications since that time. Such changes were dictated by operational difficulties or need of specific experimental results.

After discussions with other experimenters and a review of test units reported in the literature, the author adopted three basic premises in the design of the flow sheet. The first consideration was to maintain, as nearly as possible, a constant slurry throughout the system, which necessitated careful design of pipes, flumes and vessels to eliminate undesirable holdup allowing the solids to settle out. Where surge vessels were required, an attempt was made to provide sufficient agitation to preclude settling of the larger particles. Many testing units of this type have proven quite difficult to run, in that too ambitious a scale has been used, thus requiring



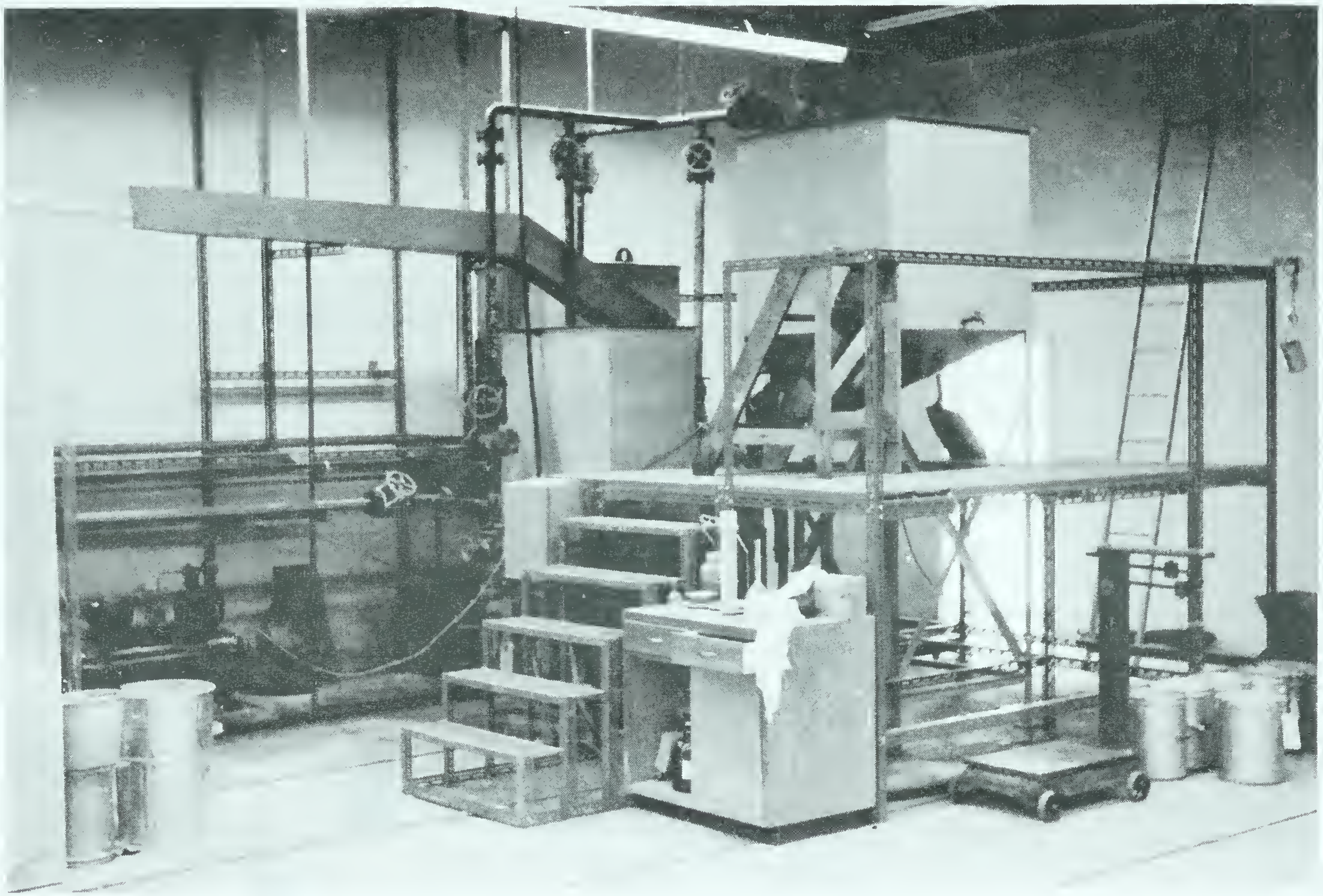
FLOW DIAGRAM
EXPERIMENTAL EQUIPMENT

FIGURE II - 1

several operators at any time. The system as erected can be operated for the most part by one man and, in some series of tests, requires an additional man.

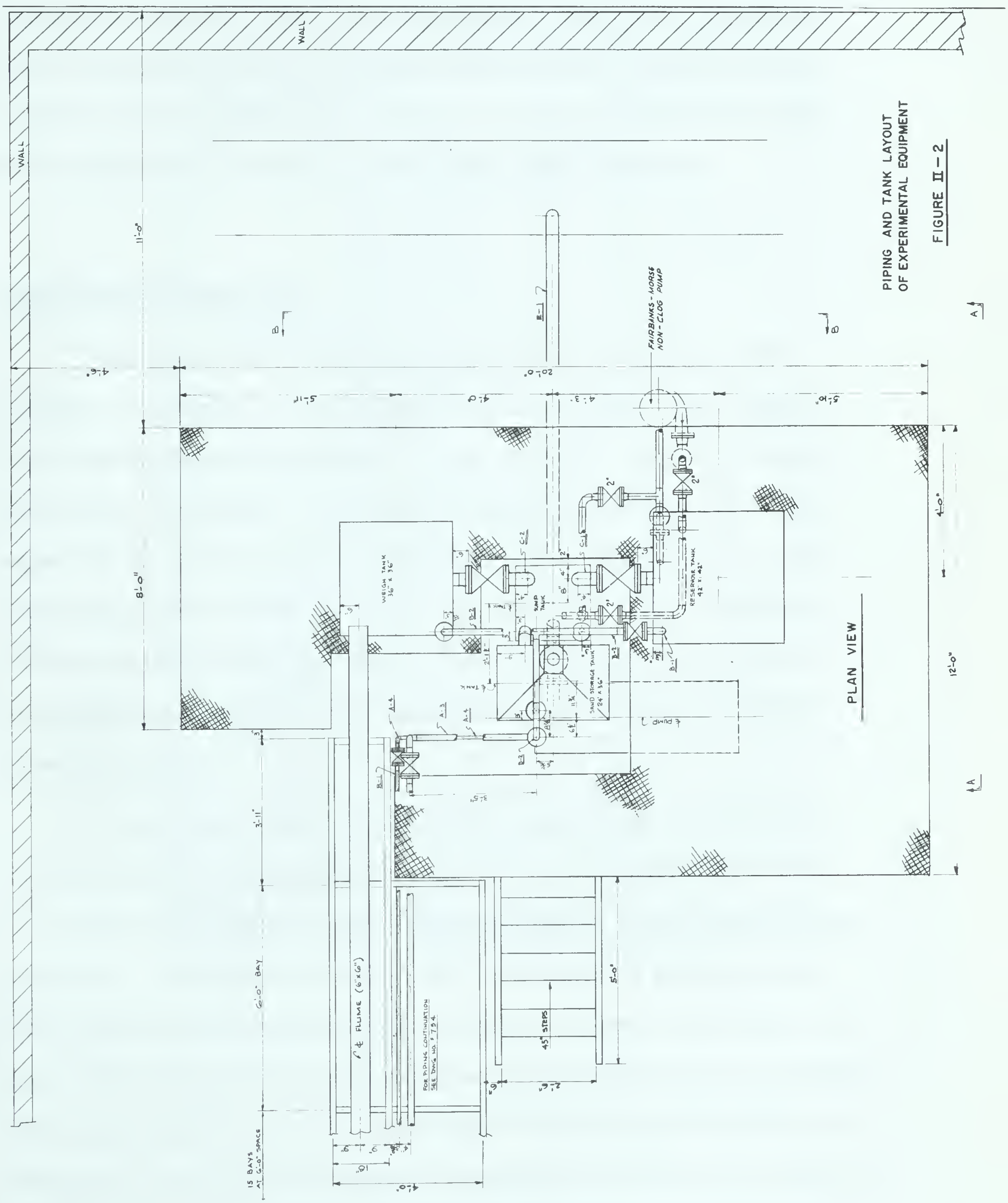
The most important item in designing the equipment was that of instrumentation. At the outset, the philosophy was to install the simplest possible instrumentation and gather only those data considered absolutely necessary. It was felt that modifications could be made as the experimental program proceeded and that experience would be the best guide. Accordingly, only manometers, simple staff gauges and a weigh tank were installed in the original system.

The circulating pump takes direct suction from the sump tank and transfers the slurry through the test pipe section in either the 1" or the 2" test pipe and either via the flume or the return pipelines to the sump tank. The original design contemplated that all slurries would be handled in the flume for return. However, it was found that the flume could not handle dense sand-water slurries and return pipelines were installed. A simple manometer system was originally installed on both the 1" and the 2" test pipes but was later completely revamped for the 2" pipe. When a discharge measurement was required, a large sample of the total discharge was caught in a weigh tank over a long period of time to measure both the weight and volume discharge rate. When the stream was intercepted by the weigh tank, the sump tank level began to fall, thus decreasing the head on the intake of the sand pump. A reservoir tank was included in the system to alleviate this difficulty, allowing the sump tank level to be maintained by taking makeup from the reservoir tank.



EXPERIMENTAL EQUIPMENT LAY-OUT SHOWING TANK GROUPING

PLATE II - I



PIPING AND TANK LAYOUT OF EXPERIMENTAL EQUIPMENT

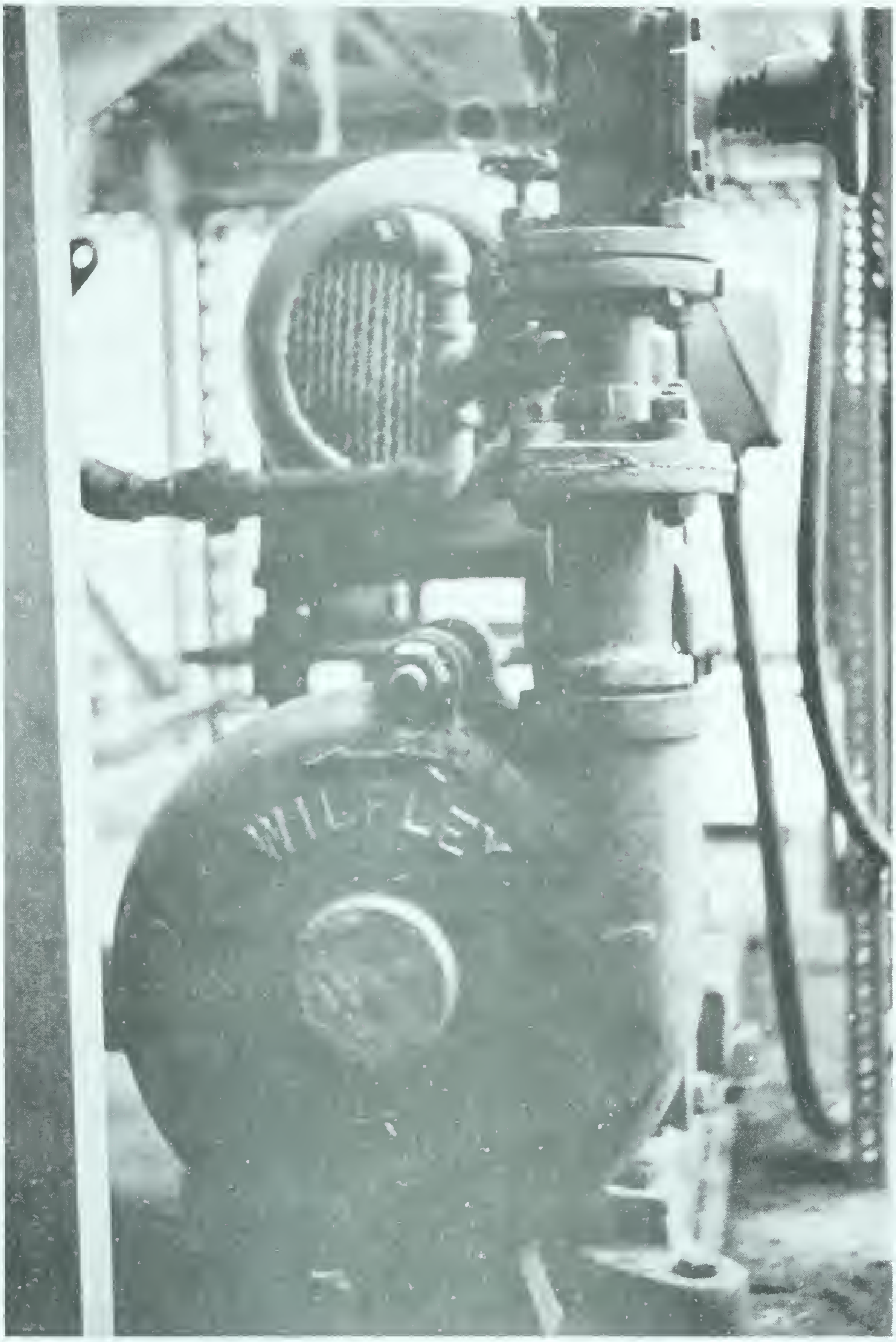
FIGURE II – 2

For the most part, the circulating fluid was either a two- or three-component mixture of water and fines, water and sand or a combination of both. No direct laboratory measurement could be found to analyse the slurry directly and therefore repeated representative grab samples were taken for subsequent analysis in the Soils Mechanics Laboratory of the University of Alberta.

2.2 Experimental Apparatus:

The experimental apparatus was designed by the author, with the cooperation of the sponsor's technical staff. The equipment was fabricated locally and set up in the University of Alberta Hydraulics Laboratory. PLATE II-1 shows the tank grouping and operating deck of the experimental apparatus. FIG. II-2 is a plan of the piping and tank layout of the equipment as it was installed. This has recently been modified. Additional pumps were added, necessitating a complete rearrangement of the tankage and interconnected piping.

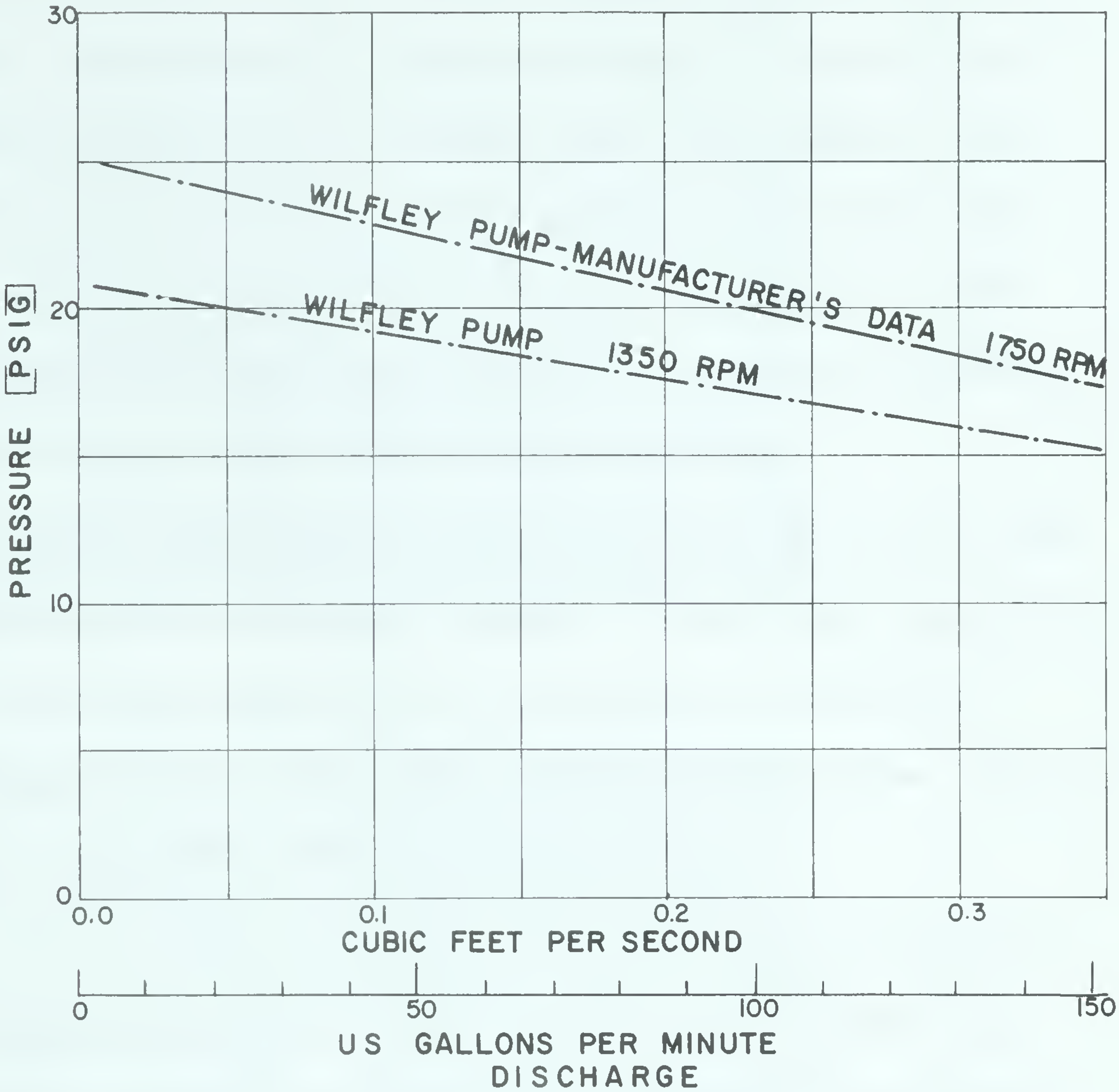
A 150 U.S. GPM, 4" x 2" Wilfley sand pump (PLATE II-2) was used in the experimental system. It was driven at 1350 RPM by a 10 HP, 1725 RPM electric motor through a V-belt speed reduction drive. The pump operated quite satisfactorily throughout the entire program and required only occasional minor servicing to remove debris which had been inadvertently introduced into the system. The pump impeller is of the centrifugal shrouded type (PLATE II-3). During the experimental program a characteristic curve was derived for this pump and is shown on FIG. II-3, where it is compared to



END VIEW OF WILFLEY PUMP

PLATE II - 2

FIGURE II-3



CHARACTERISTIC CURVES FOR WILFLEY PUMP

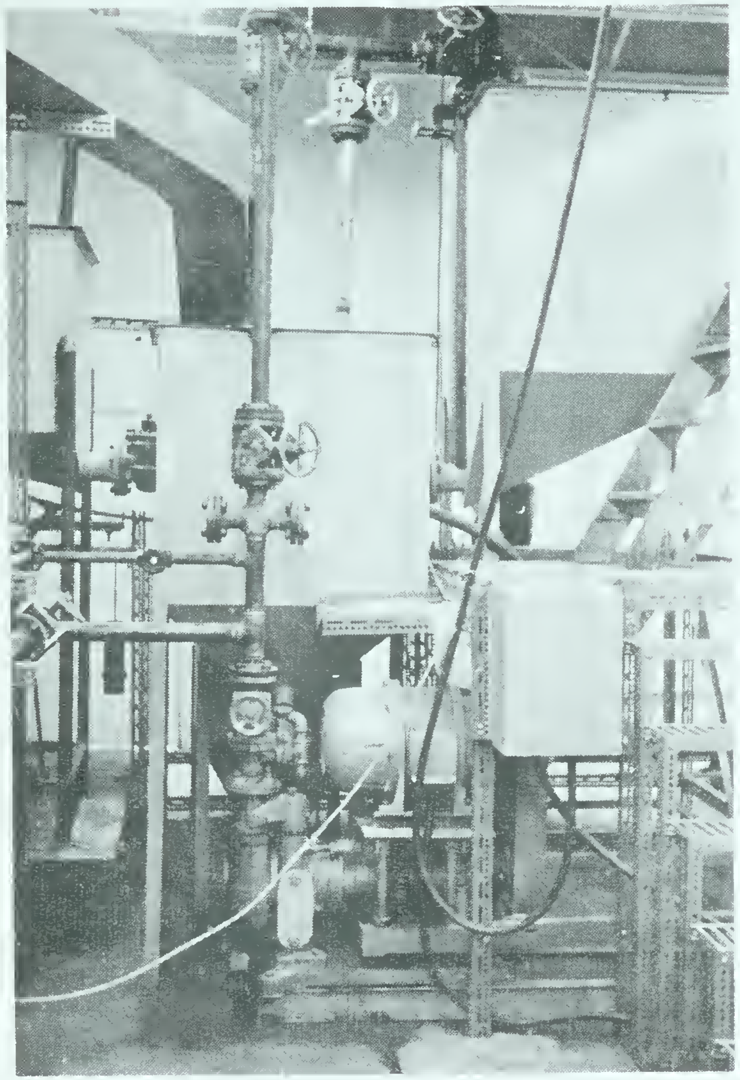
WILFLEY PUMP IMPELLER

PLATE II - 3

the manufacturer's pump curve. The discrepancy between the two curves is due to the difference in operating speeds. Two additional identical Wilfley pumps have been added to the system and all three pumps will be used in the continuing research program, but to date all test runs were conducted using only the original pump. A 150 U.S. GPM vertical Fairbanks-Morse pump was included for tankage exchange and flushing but was used in only a few tests.

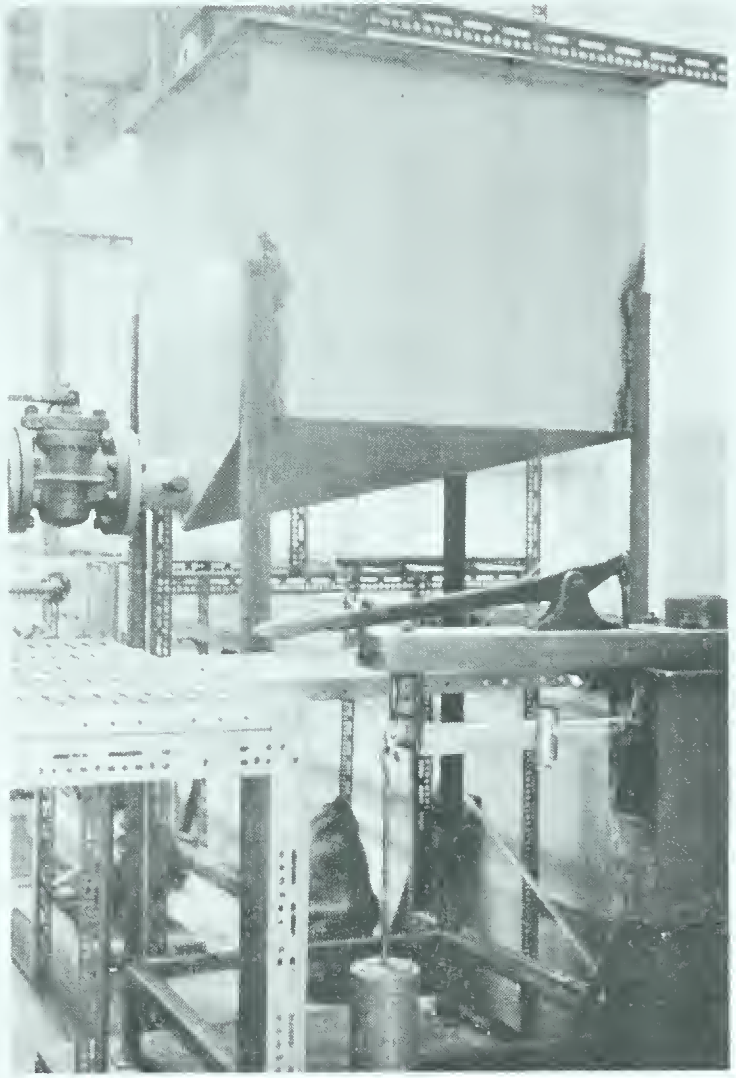
The capacity of the various tanks can be seen in FIG. II-1 and photographs are shown on PLATES II-4/5/6. All the tanks were of rectangular steel construction with a converging prismoidal-type bottom. In some instances, the square corners caused minor hang-up of solids but no major difficulties were encountered.

The 100 U.S. gallon sump tank was fabricated to the specifications of the pump manufacturer and operated very satisfactorily over the full range of slurry concentrations encountered in the experimental program. Even at slurries as high as 35% solids by volume, there was no bridging of solids over the bottom withdrawal, although the author suspects some surging took place in the system due to short-term sedimentation in this tank. This can be effectively reduced by top withdrawal - bottom injection recycle, using one of the auxiliary Wilfley pumps. Throughout the program, the bulk of the solids was introduced into the system at the sump tank. It was a fairly simple matter to shovel sand or pulverized fines into the tank until the desired concentration of solids had been reached. The free-fall of the return lines into the sump tank caused considerable air entrainment and slight frothing on the top of the tank. At times this air entrainment became apparent in the plastic inspection section of the pipeline.



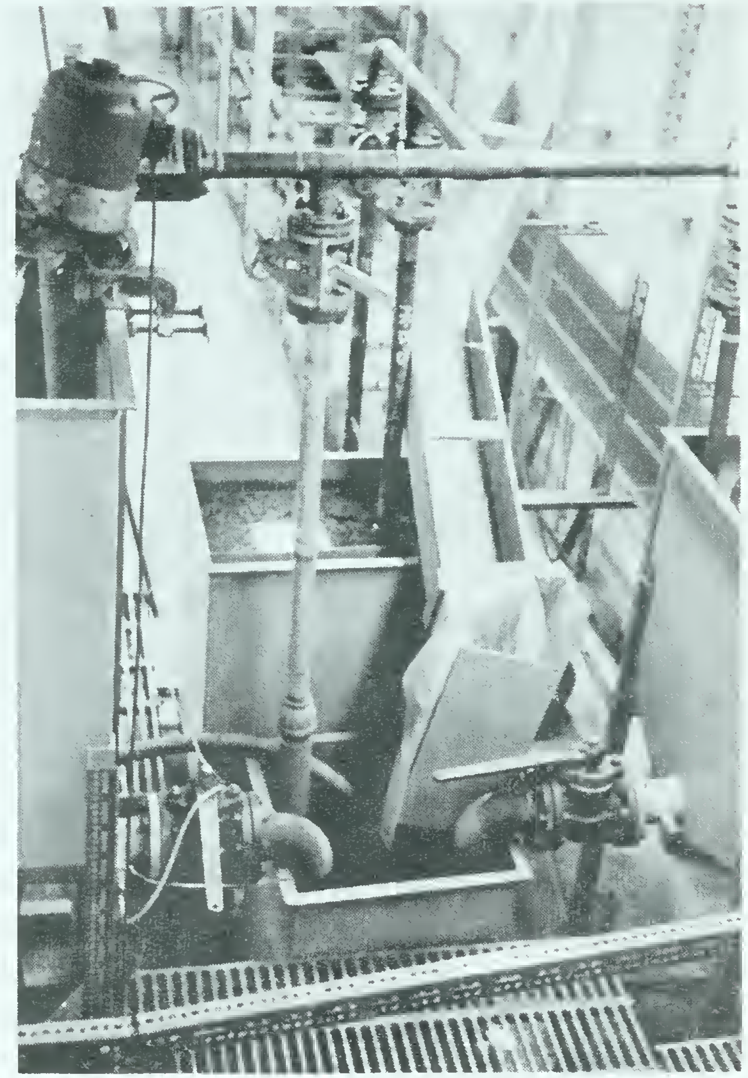
RESERVOIR TANK

PLATE II - 4



WEIGH TANK AND SCALE

PLATE II - 5



VIEW OF TOP OF SUMP TANK. SHOWING OUTLETS FROM RESERVOIR TANK ON THE LEFT, WEIGH TANK ON THE RIGHT AND FLUME BY-PASS.

PLATE II - 6

The reservoir tank was built with a capacity of 375 U.S. gallons and was designed to retain the entire slurry inventory of the system. At the completion of a day's operating, the pump was used to transfer all the material into the reservoir tank. As previously discussed, the reservoir tank was included as a source for makeup to the sump tank during discharge measurement in the weigh tank. Since it was necessary to introduce makeup slurry of similar characteristics to that of the recirculating system, the tank was equipped with two $\frac{3}{4}$ HP, 440 RPM Lightning mixers, each with two sets of turbine blades. A separate pump-around system employing the Fairbanks-Morse pump was also useful in maintaining violent agitation in the reservoir tank to prevent the coarse fraction of solids from settling-out.

The 115 U.S. gallon sand tank was included into the system for in-line storage of solids. The original design feature was that water from the system could be pumped into the bottom of the tank, thus fluidizing the sand within it and carrying a thin slurry over the weir into the sump tank. Unfortunately, this could not be realized in operation. However, the tank did serve an extremely useful purpose on occasion as an elutriation vessel for separating the fines from the sand.

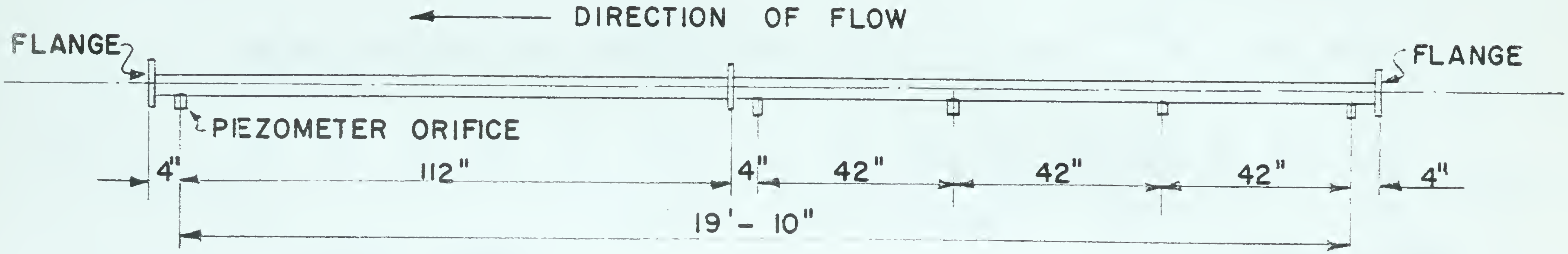
The weigh tank was designed to take a large sample of the complete stream for weight and volume determinations. Flow from the flume and both 1" and 2" return lines could be diverted from the sump tank into the weigh tank. A 225 U.S. gallon tank was set on a Fairbanks-Morse 5000-lb. capacity scale. This scale was inspected

and maintained by the manufacturer on a monthly basis. Depth measurements were taken in the tank, using both a manometer and direct depth determinations using a rule.

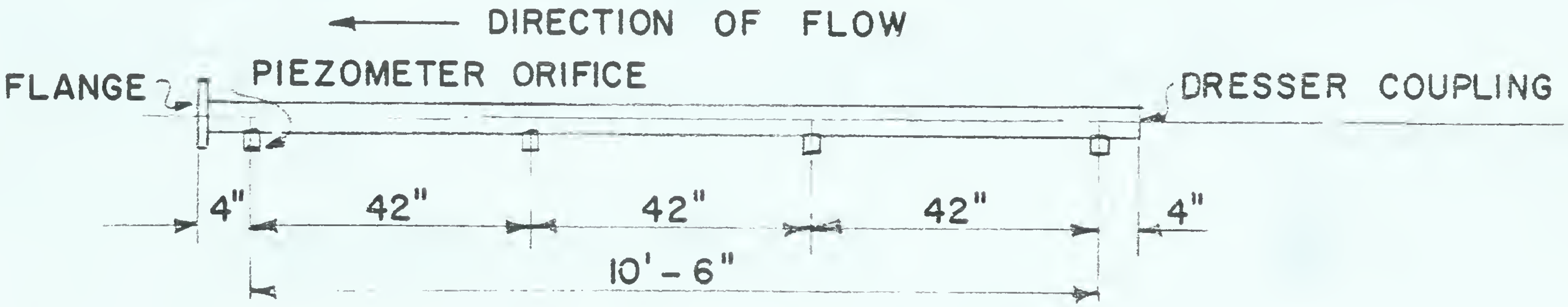
The underflow from the weigh tank and reservoir tank, as well as the overflow from the sand tank, moved by gravity into the sump tank. As can be seen on FIG. II-1, suitable piping was installed for transfer of material between any of the tanks. The original installation was quite ambitious in that different types of piping materials were installed and a test section of fittings such as welded, flanged and screwed couplings, valves and a venturi were included. Extreme difficulty was experienced in keeping the manometers operational for this section and, after a few abortive attempts, all readings were deemed unreliable and the fittings test section was removed from the pipeline.

The original 2" pipeline contained two test sections, each 10.5 feet long, equipped with four equally-spaced piezometer orifices. FIG. II-4 shows a piping diagram giving the details of these test sections.

After the system had been operated approximately one year, the 2" pipeline was changed to incorporate a new test section and a new manometry system. Three test sections were connected in series, as shown on FIG. II-5, the first of which was approximately 15 feet downstream from the discharge of the Wilfley pump. A transparent section of plastic pipe was included in both the original 2" and the final 2" pipelines for visual inspection of the flow. The connecting bars between the flanges of this plastic pipe were included



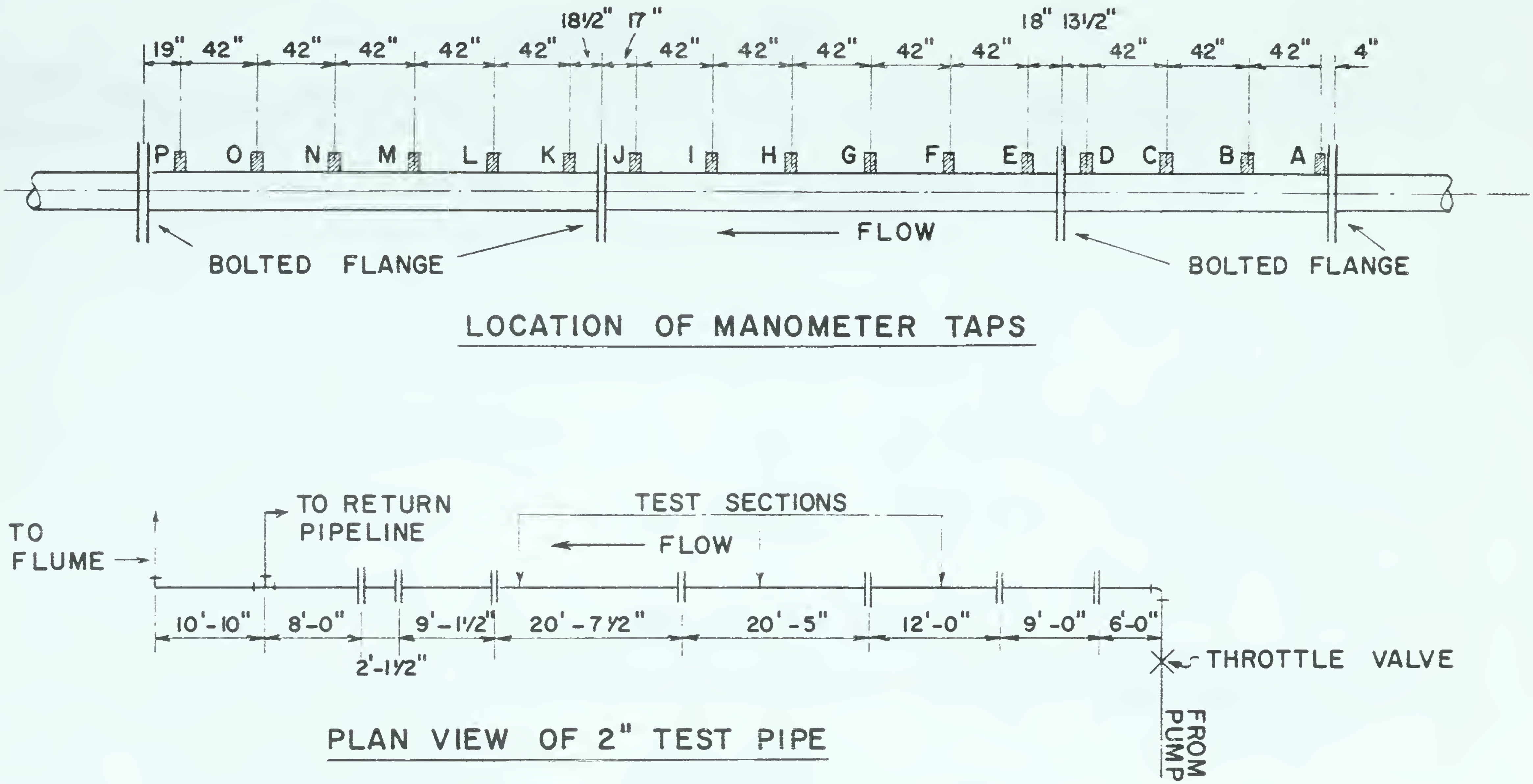
INITIAL 2" SCH. 40 STEEL TEST PIPE



2" ALUMINUM TEST PIPE

INITIAL 2 INCH TEST PIPE

FIGURE II – 4

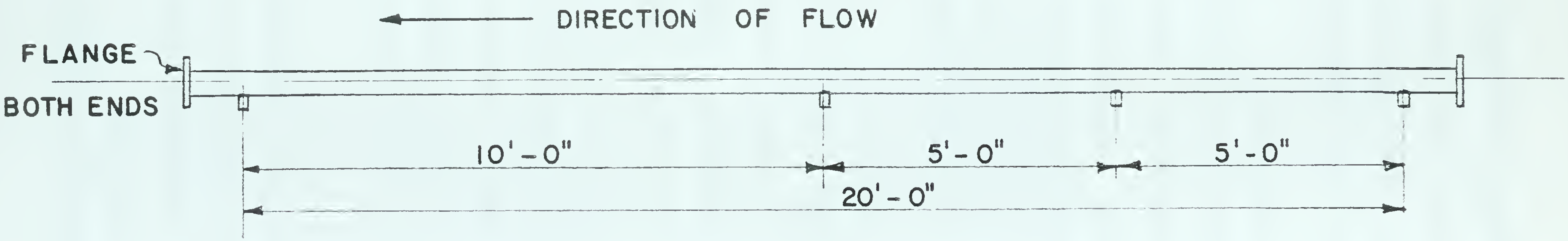


LOCATION OF MANOMETER TAPS

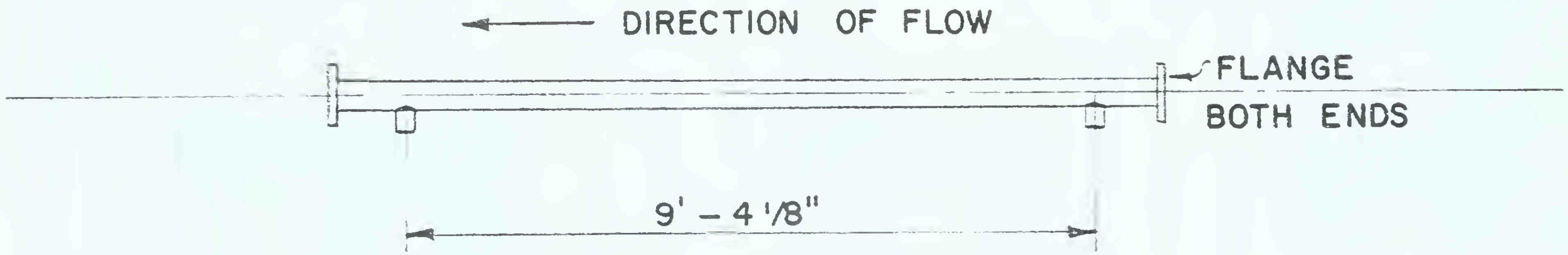
PLAN VIEW OF 2" TEST PIPE

MODIFIED TWO INCH TEST PIPE
– LOCATION OF MANOMETER TAPS
AND PLAN VIEW –

FIGURE II – 5



1" SCH.40 STEEL TEST PIPE



1" ALUMINUM TEST PIPE

1" TEST PIPE

FIGURE II - 6

to eliminate cracking of the plastic, which was originally encountered. This inspection section, shown in PLATE II-7, proved to be invaluable in determining whether the slurry was staying in suspension or a bed was forming on the bottom of the pipe.

The 1" test pipeline included two test sections, one of Schedule 40 steel pipe and one of aluminum pipe. The steel test section was equipped with four piezometers and the aluminum section with two. Details of this pipeline can be seen in FIG. II-6. This test pipeline was not altered and still exists as originally installed. However, readings were taken on this section only during the first year of the unit's operation.

The flume, with a 6"x 6" cross-section, was constructed of 1" finished spruce. It was made up in 12-foot sections and had an overall length of 102 feet. It was hinged between sections and supported, so that the slope could be varied from zero to 5%. A diversion channel was provided so that the flow could be directed either to the sump tank or to the weigh tank in the event that a discharge measurement was to be taken. One 12-foot section of Plexiglass flume was installed for visual inspection of flow regime and photography records of bed load behaviour. Several views of the flume can be seen on PLATES II-8, -9, -10 and -11.

The entire apparatus was supported by a Dexion framework. Walkways were provided to allow access to all parts of the system for maintenance and operation. This feature was extremely important for cleaning of the flume on occasion.

Additional photographs of the experimental apparatus are included in APPENDIX "E".

2" PLASTIC PIPE INSPECTION SECTION

PLATE II-7

VIEW LOOKING ALONG THE FLUME

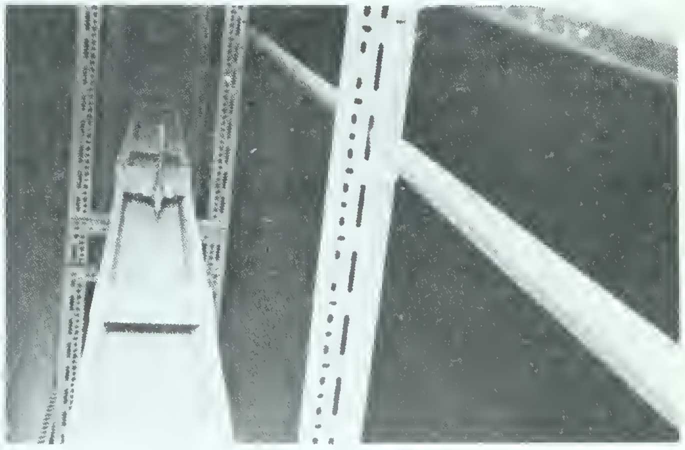
PLATE II-8

TRANSPARENT SECTION OF THE FLUME SEEN FROM BELOW

PLATE II-9

FLUME DIVERSION SECTION LOOKING UPSTREAM

PLATE II-10



FLUME GAUGING SECTION LOOKING DOWNSTREAM

PLATE II-11

2.3 Instrumentation:

The flume slope was set by measuring the height of rise at a given horizontal run of the flume. The depth of flow on the flume was measured by two micrometer depth gauges equipped with straight needle-point probes, which could be brought down to just touch the surface of the water. These gauges, which can be seen in PLATE II-11, were set 20 feet apart on the flume.

The discharge was measured by diverting the flow from the return pipelines or flume into the weigh tank for a determined length of time. The 4" underflow valve was closed prior to commencing the weighing and approximately 200 to 400 lbs. of slurry were diverted into the weigh tank, requiring a time of approximately 15 to 40 seconds, depending on the flow rate of the system. A hand stop-watch, measuring to the nearest tenth of a second, was found most convenient for the time determination. Direct depth measurements in the tank were taken by measuring from a known elevation to the surface of the water using a rule. A sight glass was provided with a standpipe mounted on the exterior of the tank for direct observation of a scale reading in inches. In all discharge determinations, care was taken to make sure that the prismoidal-type bottom of the tank was covered with an initial amount of slurry so that volume computations could be more easily carried out.

Concentrations of sand and fines were determined by analyses of grab samples. Tared 8-ounce wide-mouthed jars were introduced into the stream at the free-fall discharge of the flume or return pipeline. Considerable care was taken to fill the bottles only partially,

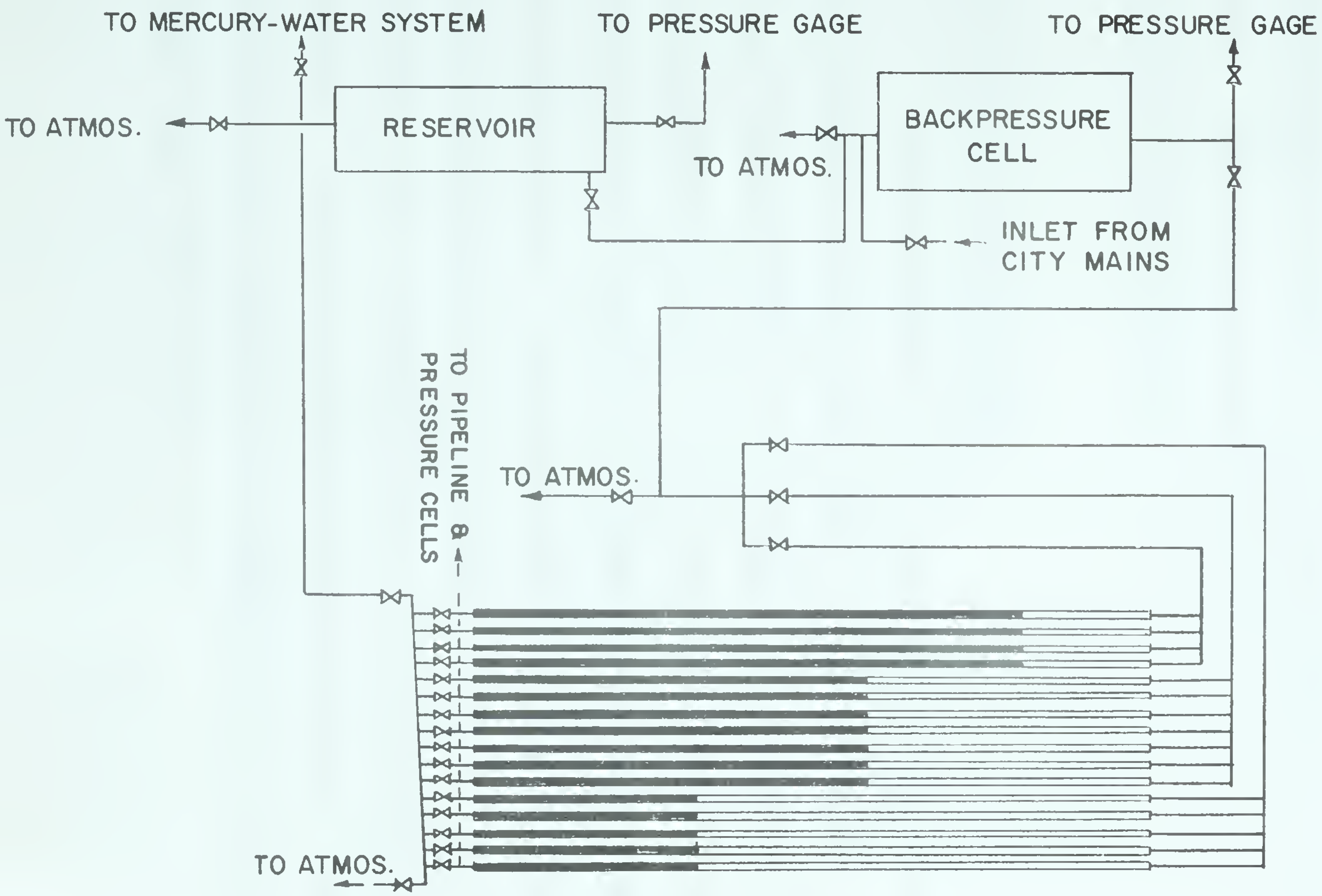
to avoid an increase in solids concentration by overflowing the fluid. Duplicate samples were taken for each run and the samples were weighed and then placed, open, in an oven for at least 48 hours at 105° C (repeated weighing showed negligible decrease in moisture after 48 hours). The oven-dried solids were then weighed. In the case of a two-component mixture, concentration by weight was determined. However, in the case of three-component mixtures, it was necessary to separate the components. After dry-weighing was complete, the solids were re-slurried using a high-speed mixer and then wet-sieved through a 200-mesh screen (U.S. Standard) with a considerable excess of water. Retained solids were carefully transferred from the screen, dried and weighed to determine the concentration by weight of + 200 mesh material. Concentration by weight of material passing the 200-mesh sieve was obtained by difference.

As previously discussed, the pipeline test section of 2" pipe was modified after approximately one year of operation. The original pressure drop measurement apparatus consisted of a board fitted with a series of manometers connected through Tygon tubing to manometer taps along the test pipeline. During a run, these manometers were read one by one, readings recorded and the pressure drop was subsequently calculated. For constant operating conditions, difficulty was encountered in achieving reproducibility of results due to manometer fluctuations and plugged manometer leads. Howard (1962) carefully designed a manometer system which eliminated these difficulties and yielded reproducible results.

Generally, the system consisted of a series of manometer taps connected through sediment traps to a common manometer board which could be photographed for instantaneous, simultaneous readings. A back-pressure system was installed to unplug Tygon lines by utilizing backwash. This back-pressure system could also be used to pressurize adjoining banks of manometers such that all pressure differentials could clearly be seen in one photograph. PLATE II-12 shows a view of the manometer system and FIG. II-7 shows a schematic diagram of this system.

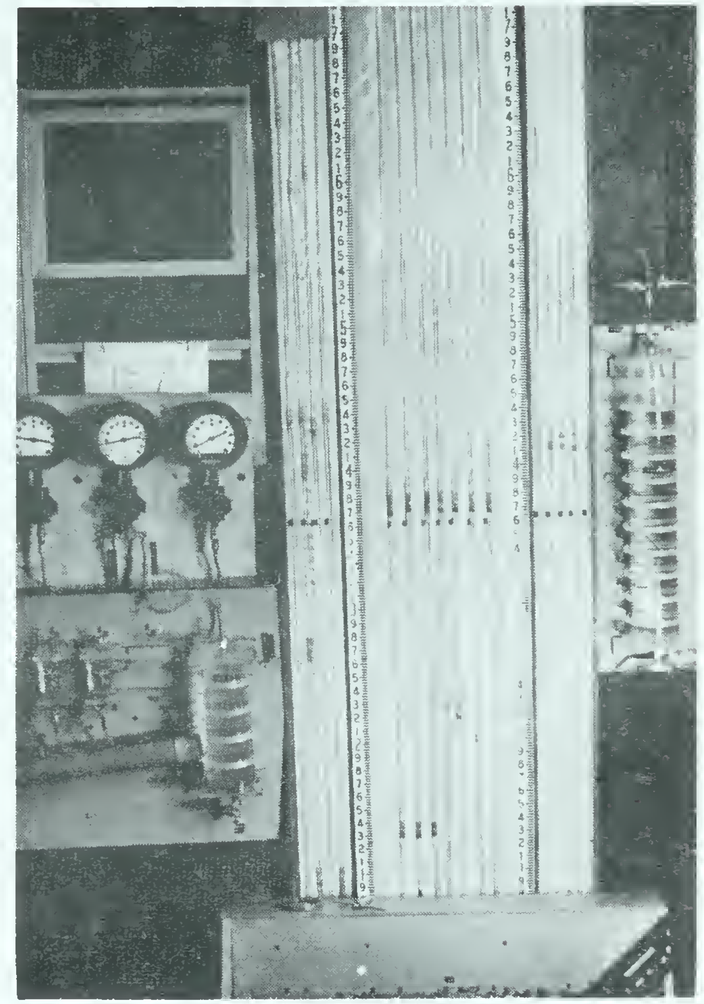
Although heat exchangers were included in the original design of the apparatus, they have not been operated in the system to date. Since the circulating fluid was stored in the reservoir tank, the slurry temperature at the beginning of a day's run was the ambient temperature of the laboratory. The temperature of the slurry would rise steadily from this point as the duration of the runs increased due to energy transfer in the pumps. The temperature was measured in the sump tank just prior to the commencement of any given run. All temperatures were in the range from 60° to 105° F and for the most part reflected the fluctuations in ambient temperature.

During each run, an inspection of the pipeline and flume was carried out utilizing the plastic section of the flume and the transparent pipe observation section, to determine the bed condition. The operator also used a probe in the flume to determine if any sand bars were building up.



SCHEMATIC DIAGRAM OF MANOMETER SYSTEM

FIGURE II - 7



MANOMETER BOARD

PLATE II - 12

2.4 Water Used for Slurry Tests:

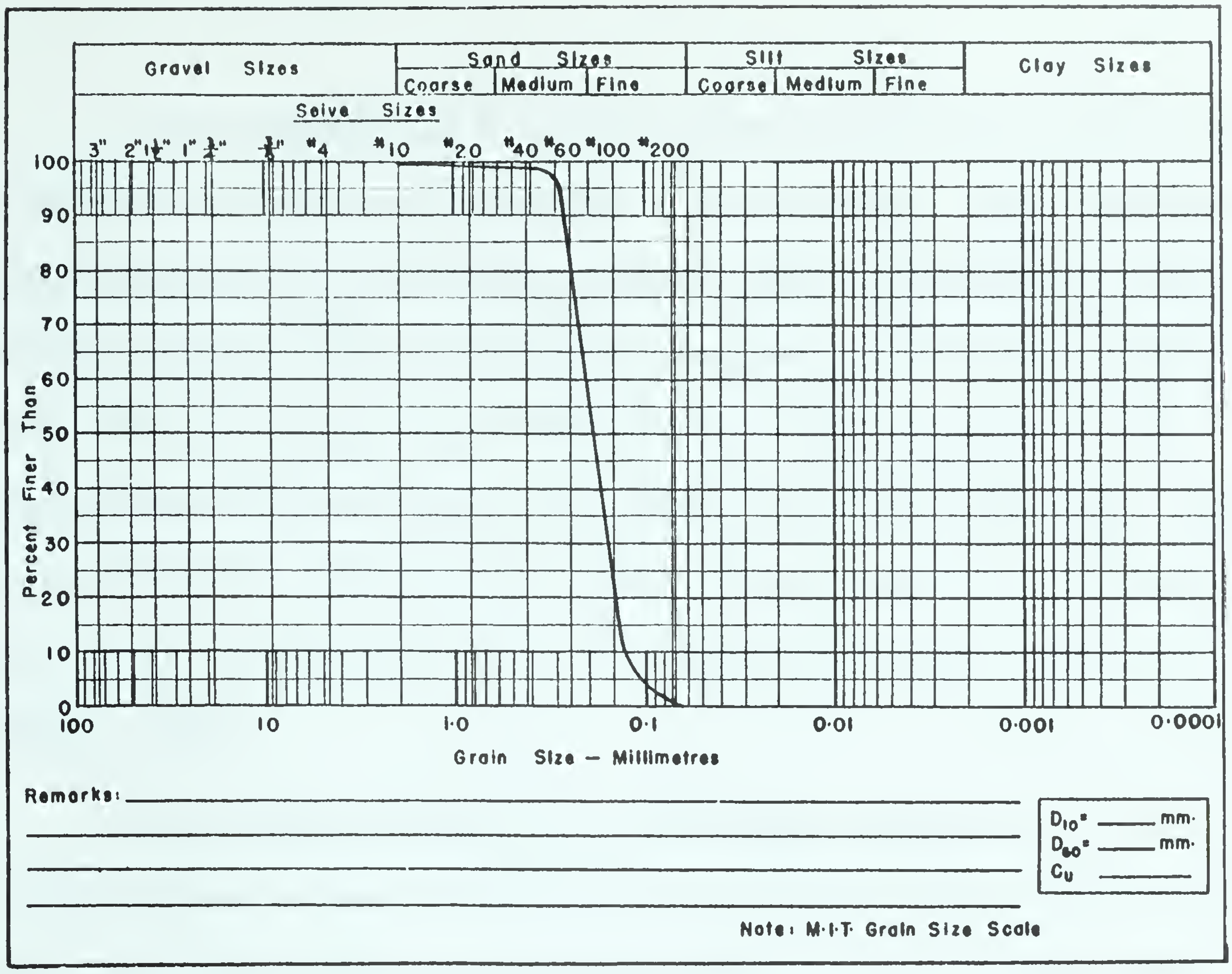
All the water used in the testing program was taken from the domestic water supply available through the water-distribution system of the City of Edmonton. A standard faucet was available immediately adjacent to the experimental apparatus. Since disposal of the water and/or slurries was inconvenient, material was kept in the system for as long as possible. The high ambient temperature of the laboratory (approximately 70° F) resulted in significant evaporation losses. Makeup was added from the domestic water supply whenever necessary. After long periods of storage, the fines-water slurries had a tendency to become stagnant and to give off a foul odour. This necessitated emptying the system once or twice during the experimental program.

2.5 Sand Used in Slurry Tests:

The sand used in the testing was supplied by the sponsor from the tailings dump of a pilot plant at Mildred Lake, Alberta. This procedure had two obvious advantages. The sand was known to have a fairly uniform size and it presented an excellent feedstock for the slurry testing in light of the proposed use of this sand in the prototype application. The sand, originally excavated as tar sand, was from the McMurray formation and, although it had been processed through a pilot extraction plant, it retained minor traces of 8.6° API bitumen. The oil-to-solids ratio (0.0005) on a weight basis indicated that only minor traces of oil were present. However, the oil was readily apparent by smell.

This sand was taken from the tailings dump, placed in barrels and transported by plane to Edmonton, where it was transferred to the University laboratory. Supplies of sand arrived at intervals during the testing program. Grain-size analyses were carried out on all these samples delivered at the Hydraulics Laboratory to ascertain if the physical characteristics of the material were similar. The initial sand shipment was sampled representatively and eight grain-size analyses were carried out, using dry-screening. The mean of the median diameters (50% finer than) for the eight samples was 0.223 mm., with a standard deviation of 0.0164 mm. Analyses of samples from subsequent shipments showed minor variations but only one had a median diameter variation of more than twice the standard deviation reported above. Grain-size analyses were carried out on sand which had been used in the test unit for extended periods. Because of the random variations, it was difficult to determine any quantitative evaluation of progressive attrition. Two of the grain-size analyses can be seen in FIG. II-8, which shows minor variations in the grading curves. It was concluded that the material could be considered essentially constant throughout the entire testing program.

The grain size data of FIG. II-8 were obtained using a dry-screening technique. A wet screening of this sand was carried out by washing the sand in a 1 : 1 mixture of isopropyl alcohol and toluene through a nest of screens (40, 60, 80, 90, 100, 120, 140, 150, 160, 180, 200, 325) into a litre beaker which retained the wash liquids. Although the wet-screening indicated that some samples contained up to 10% minus 200 mesh material, the bulk of the samples contained 3 - 5% minus 200 mesh.



GRAIN SIZE CURVES

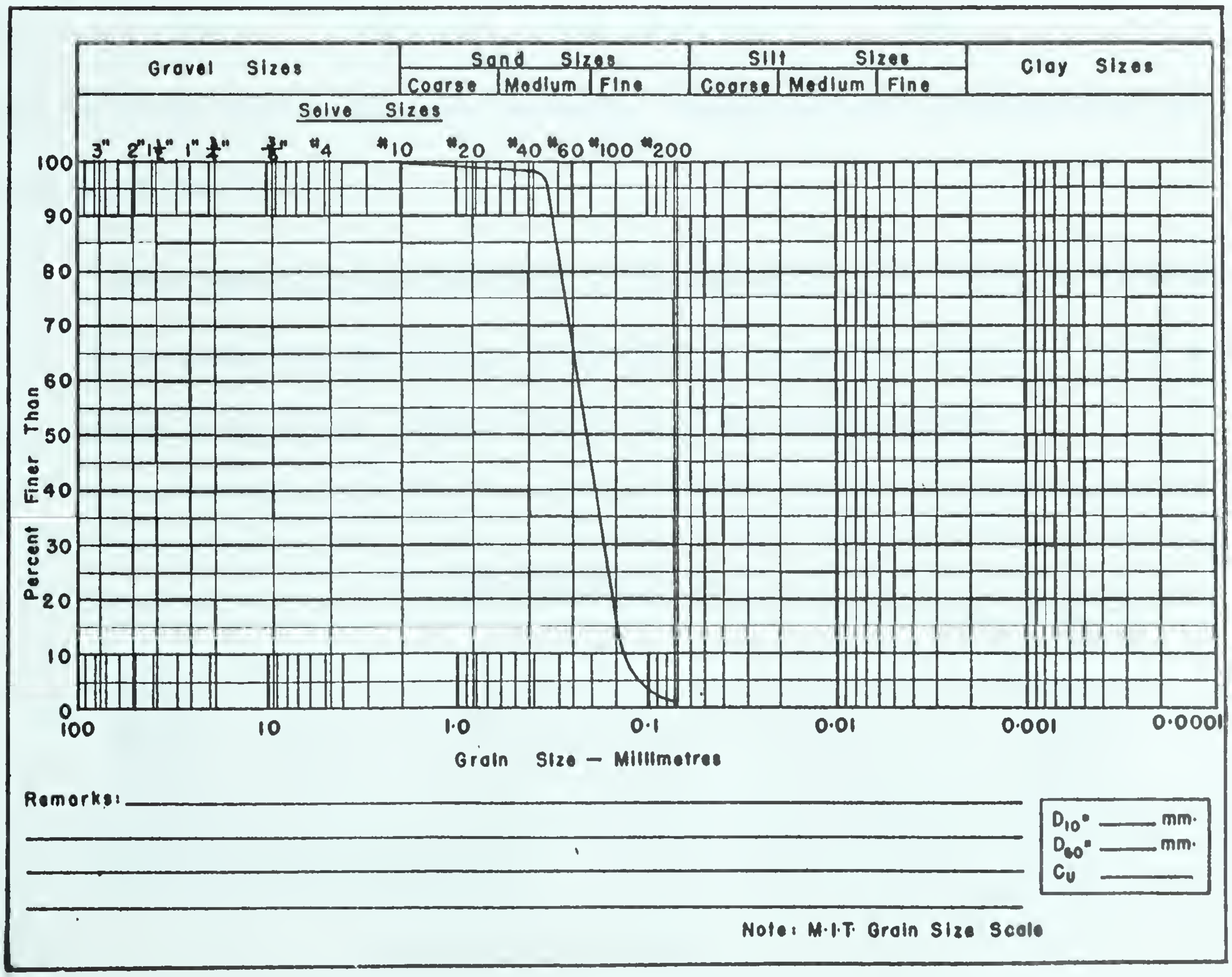


FIGURE II - 8

A non-dimensional frequency analysis was made on the results of the sieve analyses of the original eight samples. These data have been plotted on FIG. II-9 in the manner advocated by Blench (1952), with the exception that the complete frequency analysis is included rather than only in the range 2% to 98%, as recommended. The straight-line fit is excellent in the range 5% to 85% finer than, which represents 80% of the sand by weight. This sand, then, exhibits the grain size of bed load material to be expected in canals and rivers (Blench, 1957).

As previously mentioned, the abrasive action of the sand is one of the most critical design features of a hydraulic transport system. Bergeron (1952) has stated that the pertinent variables which affect abrasion are: velocity of transport, particle size, concentration of solids, imperfections of conveying pipe and materials used in pipe manufacture. The author believes that two further variables may be even more critical: namely, chemical and geometrical properties of the sand.

The chemical properties of the sand may be seen in TABLE II-1. It is possible to assign a hardness to quartz (Perry, 1953) and thus relate it to other solids which may be transported.

TABLE II-1

	Per Cent
SiO_2	95.50
Al_2O_3	2.25
CaO	0.50
Fe_2O_3	0.35
MgO	0.23
Less Loss on Ignition	1.50
	100.33

(After Ells, 1927)

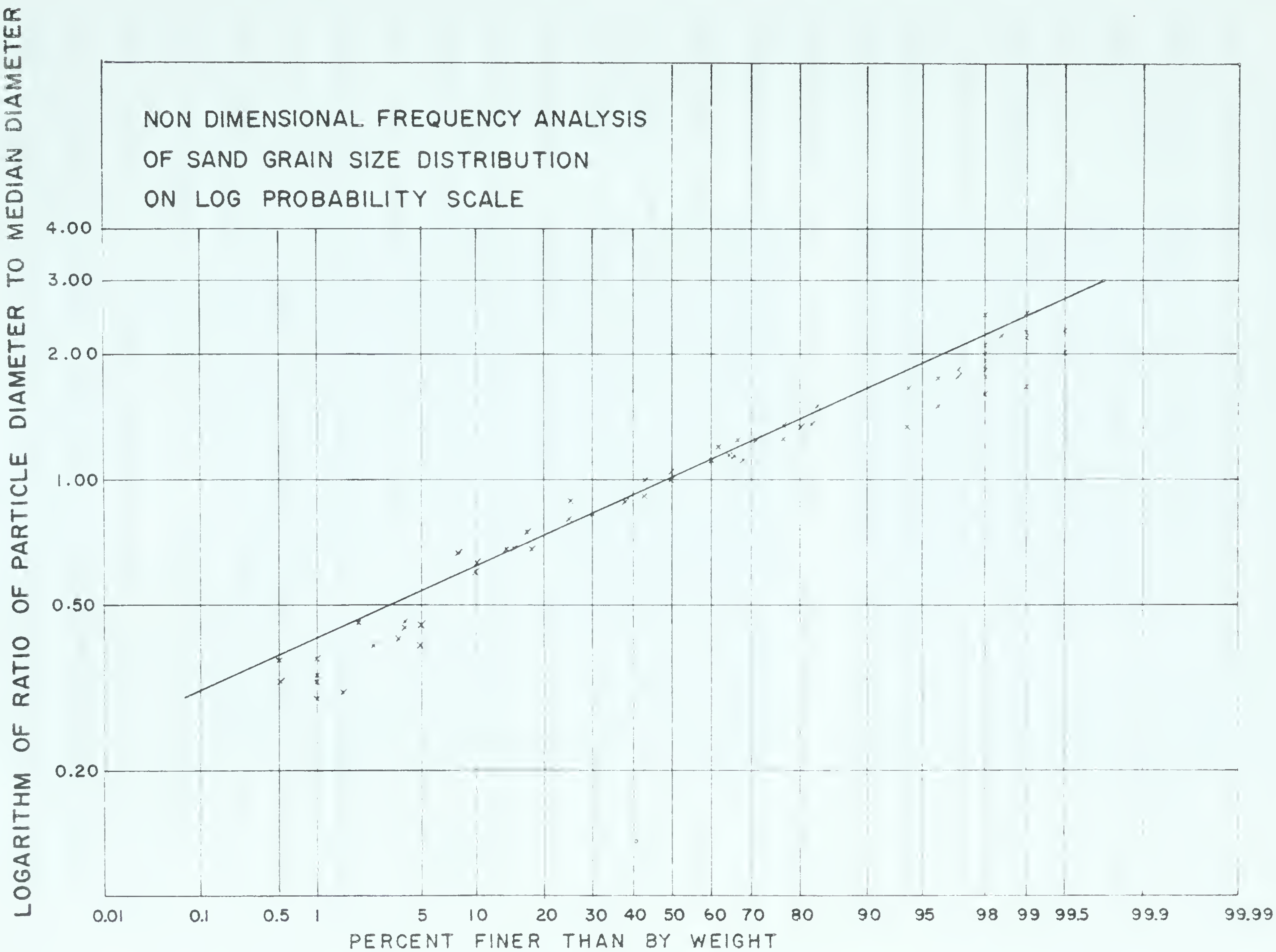

NON DIMENSIONAL FREQUENCY ANALYSIS
OF SAND GRAIN SIZE DISTRIBUTION
ON LOG PROBABILITY SCALE
LOGARITHM OF RATIO OF PARTICLE DIAMETER TO MEDIAN DIAMETER
4.00
3.00
2.00
1.00
0.50
0.20
0.01
0.1
0.5
1
5
10
20
30
40
50
60
70
80
90
95
98
99
99.5
99.9
99.99
PERCENT FINER THAN BY WEIGHT

FIGURE II - 9

The geometrical properties of the solids are much more difficult to classify due to the random variations of each particle and the very general classification system now in use. Hardy (1960) has stated that this sand is sub-angular to rounded. This identification, however, has little to offer in predicting abrasive effects. A laboratory method for predicting abrasion rates using radioactive inserts in pipes has been developed, but the results are very inconclusive and the testing period required is extremely long if any measurable effects are to take place (Babcock, 1962). The author prefers to compare the sand used for the testing with a similar material for which erosion data are available. PLATE II-13 is a photomicrograph of the sand used during the testing. Some minor discoloration can be seen on the individual particles due to the presence of bitumen. PLATE II-14 shows a comparison of the test sand with two different sands for which data are available on erosion rates. Both the comparative sands were pumped via dredge on to highway embankments during harbour reclamation work in New York City. The sand was pumped as a slurry of approximately 15% solids by volume in salt water, through a 16" diameter steel spiral-weld pipe. Some 14,000,000 cubic yards (measured as laid down in place) of Sand A were transported through the system and the pipeline was still serviceable. Sand B was then handled in a similar manner through the same pipeline. This material wore through the pipeline after delivery of only 100,000 cubic yards of material. This does not mean that the erosion rate with the coarser sand would be 140 times greater than with the finer sand, since the pipe had undergone considerable wear in the prior

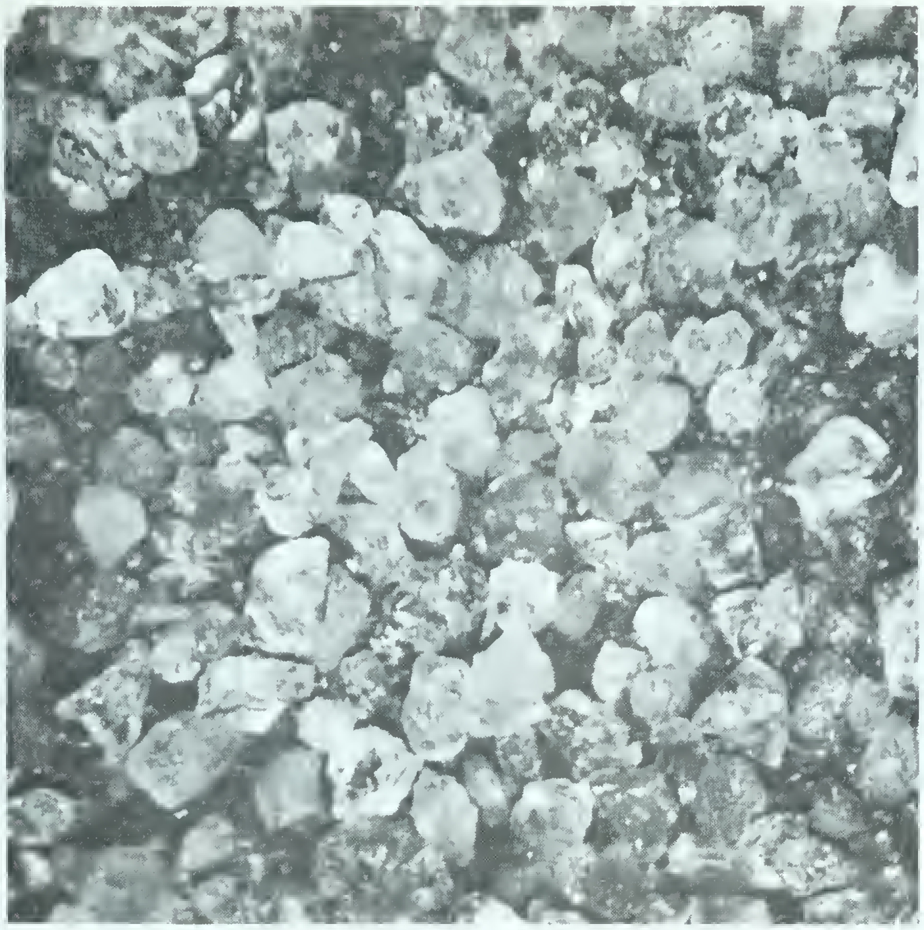
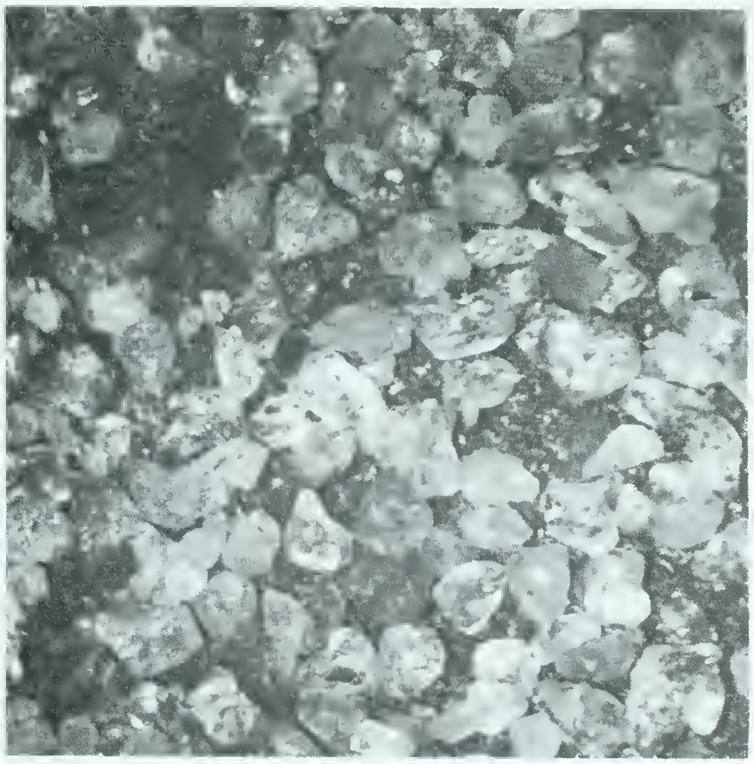
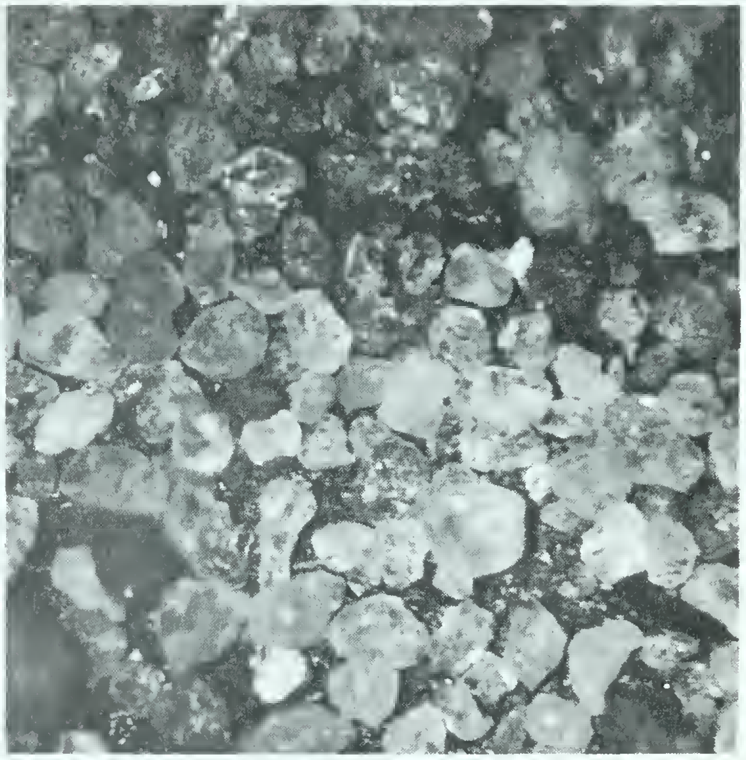


PHOTO-MICROGRAPH OF TEST SAND

PLATE II - 13

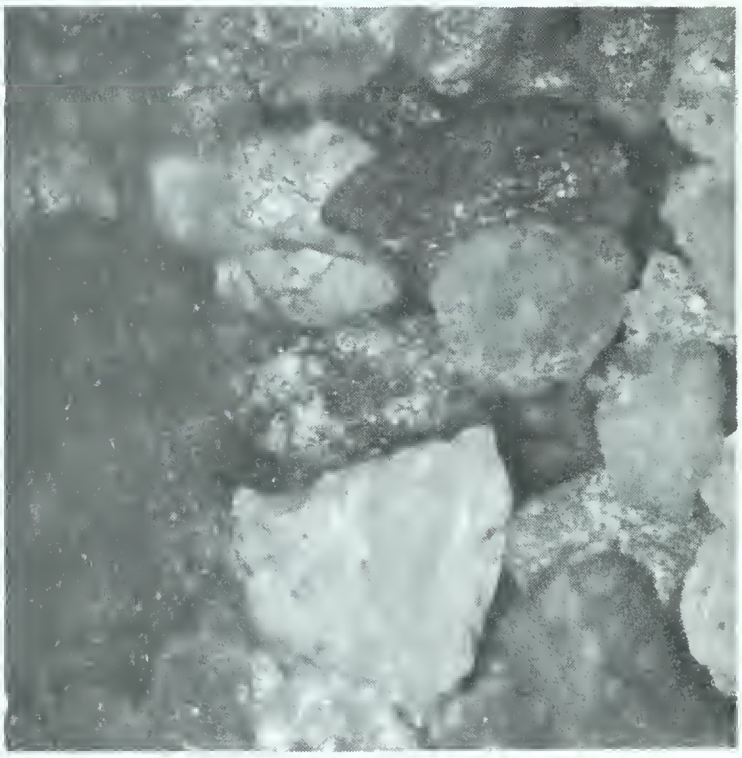


ALBERTA TEST SAND



SAND "A"

SCALE



SAND "B"

COMPARISON OF ALBERTA TEST SAND WITH SANDS HANDLED COMMERCIALLY

PLATE II - 14

dumping of the fine sand. However, the operators assured the author that, based on experience with the material, the coarser sand would wear out new pipe in less than two million yards of handling.

These data markedly illustrate the effect of particle angularity. As can be seen on PLATE II-14, the Alberta test sand is quite similar to Sand A in physical properties. The author estimates that regular steel pipe in the size range of 16" to 30" diameter will be capable of handling twenty to twenty-five million cubic yards of the Alberta test sand before replacement. This estimate is contingent on regular pipe rotation and operation at a velocity just above critical deposit velocity.

All the sand particles are water-wet, with no direct contact of bitumen and quartz. Since the bitumen has a specific gravity of 1.0099 at 60° F, there seemed no particular merit in carrying out expensive procedures to eliminate this bitumen.

Several A.S.T.M. designation D-854-52 tests were performed to determine the specific gravity of the sand. Although the specific gravity was first reported as 2.62 (Ansley and Hebbert, 1961), on the basis of some preliminary testing, more extensive work confirmed the specific gravity as 2.65, as might be expected for quartz.

2.6 Sludge Used in Slurry Tests:

An extensive series of tests was carried out on a fines-water mixture supplied by the sponsor and identified as "sludge." This material was taken as an effluent stream from the sponsor's pilot

plant at Mildred Lake, sealed in barrels, transported to the Hydraulics Laboratory and stored for subsequent use. Unfortunately, the material was frozen during the winter of 1961. However, there was no damage to the barrels and the supernatant liquid was retained.

The sludge was a dispersion of fine mineral matter, bitumen and gas-oil in fresh water, with the bitumen and gas-oil occurring as a homogeneous hydrocarbon liquid with a gravity of 20° - 25° API. The water contained 100 - 200 parts per million of calcium carbonate hardness and had a pH of 7 - 7.5. The sludge was initially a very dilute slurry with approximately 1% solids by volume and 1% hydrocarbon by volume. The sludge was thickened by decreasing the water content through evaporation.

The sludge as used varied both in solids contant and size distribution of solids. However, a typical grain-size analysis can be seen in TABLE II-2 and can, for all practical purposes, be considered representative of the material.

TABLE II-2

TYPICAL GRAIN-SIZE ANALYSIS OF SLUDGE SOLIDS
(Solids Content - 2.09% by Weight)

% by Weight Finer than	Grain Size
97.6	0.074 mm.
96.4	0.044 mm.
92.2	0.020 mm.
39.5	0.005 mm.
28.3	0.002 mm.

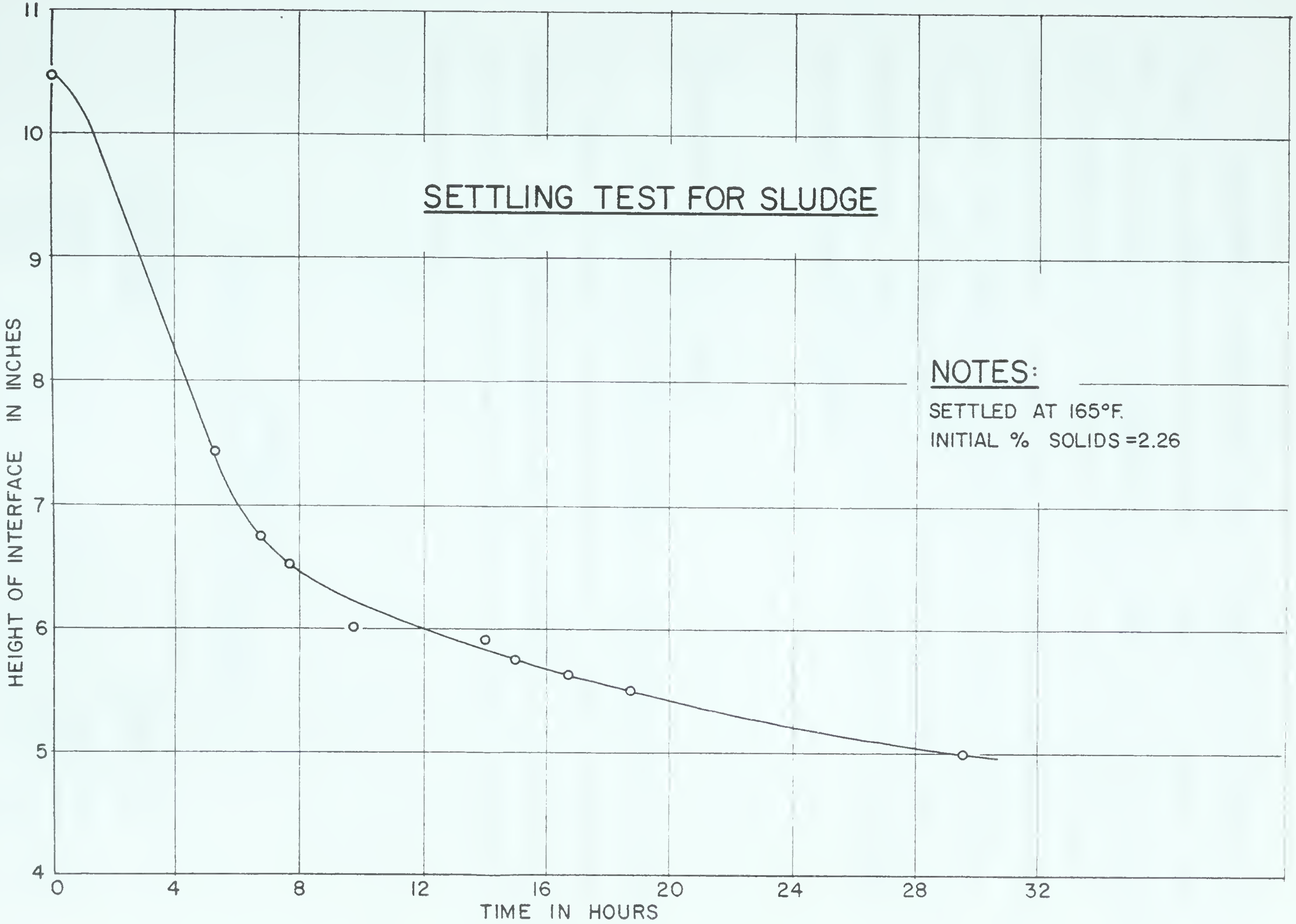

SETTLING TEST FOR SLUDGE
NOTES:
SETTLED AT 165°F.
INITIAL % SOLIDS =2.26
HEIGHT OF INTERFACE IN INCHES
TIME IN HOURS
0
4
8
12
16
20
24
28
32
4
5
6
7
8
9
10
11

FIGURE II - 10

Laboratory settling tests were conducted on the sludge to determine the settling rate of the solids for design of retention vessels. FIG. II-10 is fairly representative of the sludge used during the tests. The settling tests were carried out at 165° F, since the anticipated commercial stream would be in this approximate temperature range. The tests were conducted by putting 500-ml samples in graduated cylinders, which were placed in a constant-temperature bath. As the mineral matter settled, the level of the supernatant water interface was noted at regular intervals.

2.7 Fines Used in Slurry Tests:

It became inconvenient to obtain repeated shipments of sludge for testing work and it was extremely difficult to build up high-density sludges. After considerable study it was decided to obtain fines material from a local source and to synthesize the original material as closely as possible.

TABLE II-3

SIZE CLASSIFICATION OF FINES

% by Weight Finer than	Grain Size
98.0	0.074 mm.
92.0	0.044 mm.
87.0	0.020 mm.
72.0	0.010 mm.
60.0	0.001 mm.

The material denoted as "fines" is mineral matter which passes a 200-mesh sieve using wet-screening techniques. Clay was purchased from a local ceramics company and inspected for synthesis of sludge. A size classification of this material can be seen in TABLE II-3. A comparison of TABLES II-2 and II-3 shows that the ceramics clay contained significantly more material in the minus 5-micron size range than the sludge did. However, at high transport velocities the settling of the sludge mineral matter seemed unimportant in light of FIG. II-10 and the ceramics clay was accepted for test work on fines slurries. The reference to the material as "clay" is not in the technical sense of the word, since considerable portions of the material were outside the clay-size range and even included some plus 200-mesh mineral matter. This presented no difficulty since this material was quartz and could be separated in the elutriation tank.

A microscope study was carried out on the fines. The material was digested with distilled water and screened through a 200-mesh and 325-mesh nest of screens. A photomicrograph of the minus 200-mesh material can be seen on PLATE II-15. It was observed that a suspension in water was not very stable. After two to three hours, the supernatant water did not show signs of turbidity by visual observation. Some of the material was retained on the 325-mesh screen. This material was mostly silica with minor traces of impurities such as wood chips and tiny bits of brick. A great deal of the material was in the 1-to-5 micron range (a clay-size material). Broad-shaped particles indicated the presence of kaolinite; and platelets, in the same size

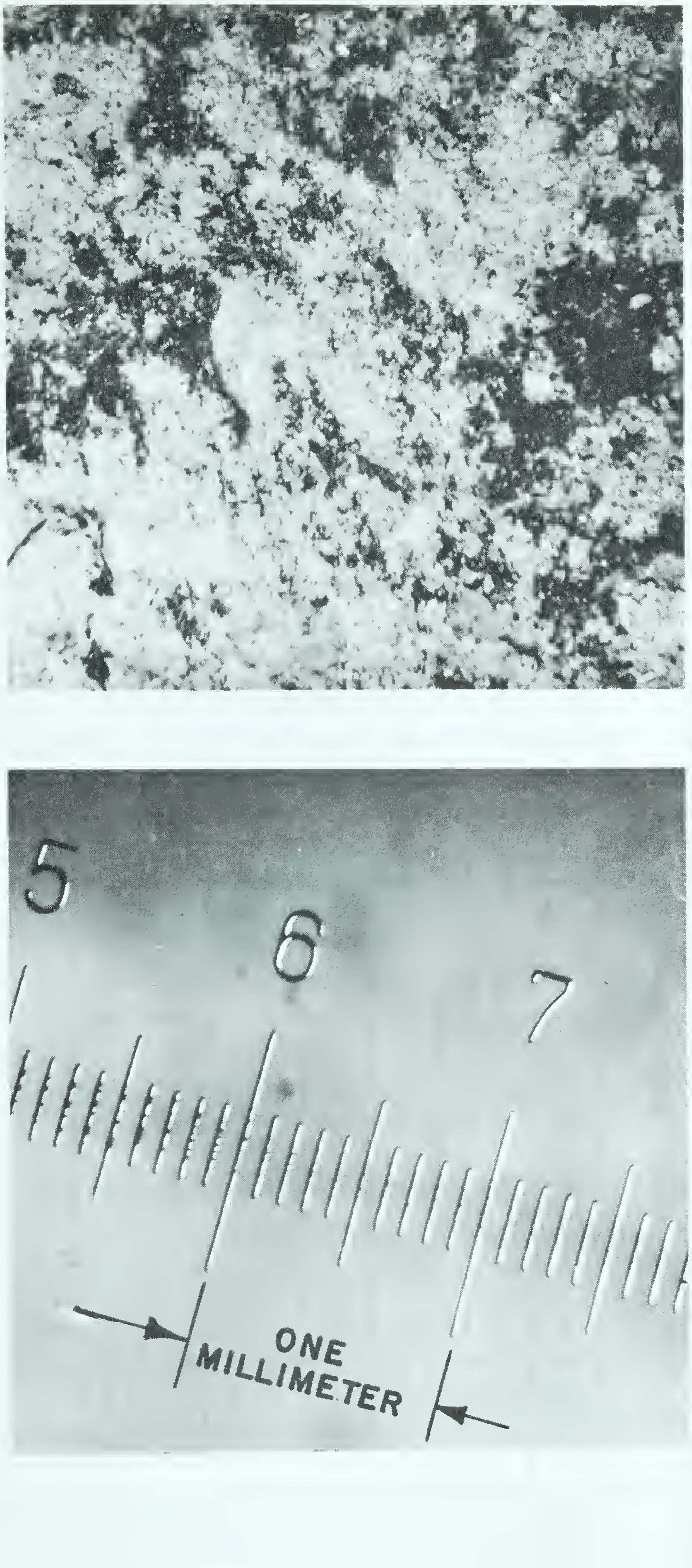


PHOTO-MICROGRAPH OF -200
MESH MATERIAL

PLATE II - 15

UNIVERSITY of ALBERTA
DEP T· of CIVIL ENGINEERING
SOIL MECHANICS LABORATORY
GRAIN SIZE CURVE

PROJECT
SITE
SAMPLE
LOCATION
HOLE DEPTH
TECHNICIAN DATE

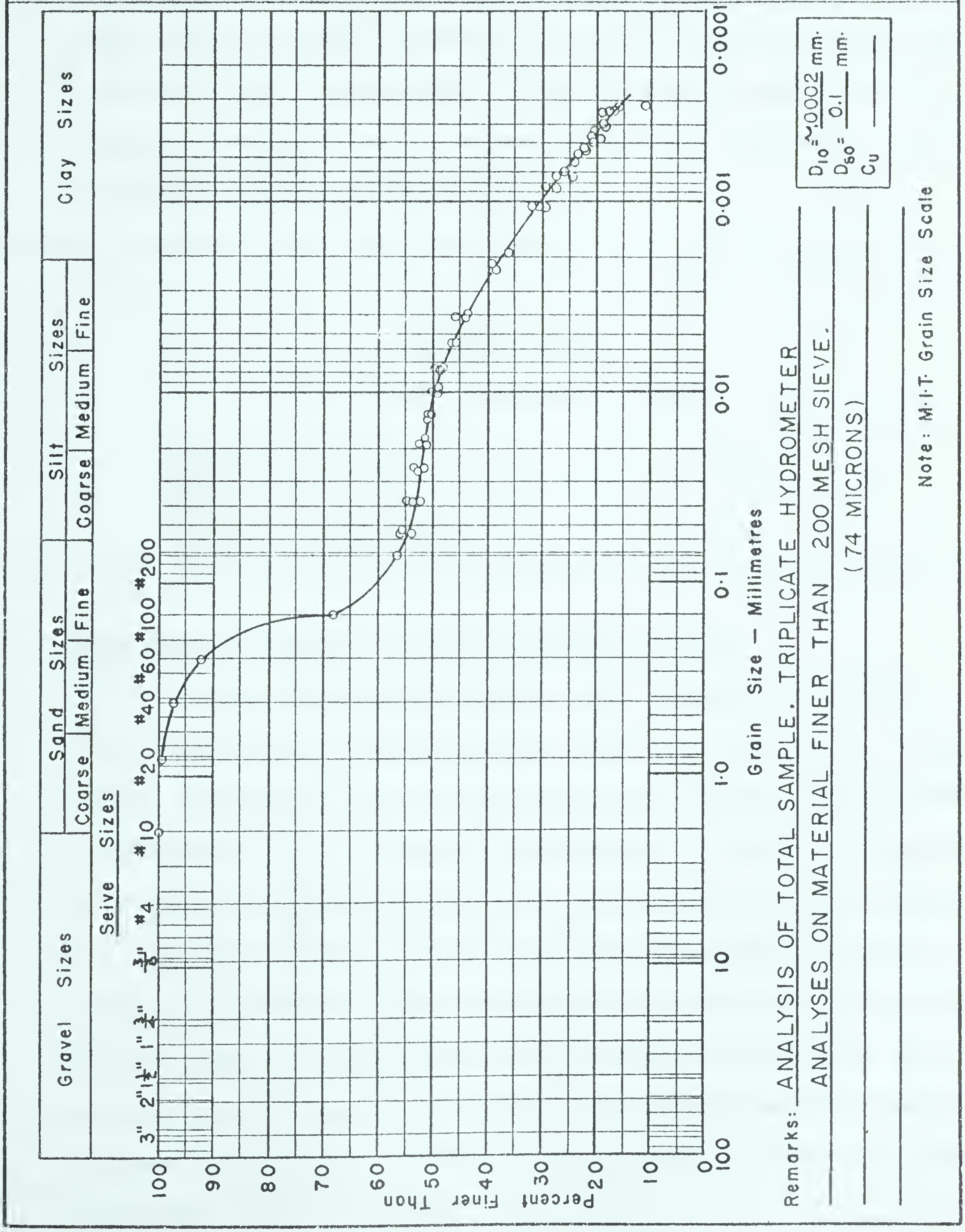


FIGURE II - 11

range, were thought to be illite. The specific gravity of the minus 200 mesh material on a dry basis was 2.71. Grimm (1953) reports the specific gravity of kaolinite in the range 2.60 to 2.68 and illite in the range 2.76 to 3.0 from one source and 2.64 to 2.69 from another source, with the low range more likely. When taking the impurities into consideration, the figure of 2.71 seems reasonable. Atterberg limits for the fines are listed in TABLE II-4:

TABLE II-4

ATTERBURG LIMITS OF FINES

Liquid limit of fines	-	39 %
Plastic limit of fines	-	19 %
Plasticity Index of fines	-	20 %

2.8 Inspection of a Sample of Three-Component Mixture:

During Phase 4 of the testing, three-component mixtures - fines, sand and water slurries, were tested in the apparatus. A typical sample was obtained from the unit and tested for grain-size distribution, specific gravity and general soil classification. A grain-size curve for the mixture can be seen on FIG. II-11, which shows the sand portion uniformly graded with the majority of the sand sizes falling in the fine classification and the solids distribution of the minus 200-mesh material as noted above. The specific gravity for the two fractions is: 2.64 for material coarser than 74 microns and 2.71 for material finer than 74 microns. The general classification of the mineral matter as a composite sample would be a clay-ey sand.

CHAPTER III

EXPERIMENTAL RESULTS

3.1 General:

This chapter includes a general review of all the data collected from the experimental apparatus. The original data were far too voluminous to be included herein, but have been processed and are listed in tabular form in the Appendices.

An account of the experimental procedures and data processing, by its very nature, is unfortunately quite lengthy and for the most part is very detailed description. In light of the continuing research program at the University of Alberta, the author feels that the inclusion of the minute detail is very necessary. A review of other workers' incomplete reporting of data in the field of hydraulic transport of fluidized solids emphasizes how important this information is if further analysis of the data is to be carried out. The bulk of the detail has been included in the Appendices to facilitate a more rapid review in this chapter.

A summarized log of each series of tests can be found in APPENDIX "A". This log outlines the type of testing, the range of results and a general commentary on the validity of the data.

The processed data are all included in APPENDIX "F". The methods of calculation of any of the listed values are summarized in tabular form, which can be examined in detail in APPENDIX "A".

All the original data were key-punched on card input for the IBM 1620 computer at the University of Alberta. Programs were written to carry out the calculations and a sample of data was processed. These calculations were subsequently checked by hand on a desk calculator. The tables shown in APPENDIX "F" are copies of the computer output.

As the program proceeded, new techniques were developed which resulted in more accurate determination of basic data. A review of the literature available on similar testing units convinced the author that concerted effort was justified in using the simple instrumentation originally installed, rather than adopting more sophisticated equipment. A discussion of the accuracy of the individual test series data is included herein. Towards the latter part of the testing program, standard techniques had been set up and the accuracy of the results was considered quite reasonable. A very comprehensive series of tests was carried out to evaluate this accuracy and is discussed in some detail in APPENDIX "B".

A rheological investigation was carried out on the sludge and fines-water slurries. A discussion of the results of this investigation is included in this chapter. Since the viscometer investigation of non-Newtonians is somewhat of a science in itself, the calibration of the viscometer and data-processing procedures are detailed in APPENDIX "C".

It is difficult to standardize a method of data presentation which can show the type of data and range of values obtained. There are over twenty tables of processed data plus three Appendices

outlining the experimental variables, accuracy of results and calculation procedures followed. A Stanton diagram of non-dimensional friction factor plotted against Reynolds number on log-log coordinates has often been used to show results for pipe data, in the manner discussed by Streeter (1958). The same approach has been used for open-channel flow data by Chow (1960). This method of presentation has therefore been used in this chapter as a reasonable standardized procedure. The individual plots are not included for detailed interpretation purposes but primarily to show the range of experimental results.

3.2 Summary of Results:

As previously mentioned, the bulk of the original data is not included herein. It is, however, available on file at the University of Alberta. The processed results are given in tabular form and should not need to be augmented by any further original data. There are more processed data available than those recorded herein, but these were not listed since they were repeat runs or obviously erroneously reported. There was, however, no attempt made to high-grade the data.

Classification of the data became somewhat cumbersome due to the testing period, extending over some three years. The system used was ultimately developed concurrently with the final calculation of processed data on the computer. All attempts at a chronological classification were abandoned, although the date of each test is included. It was more expedient to divide the data according to the

phase of the testing as the broad classification and further to delineate it as the pipe or flume equipment under testing. The four phases were classified according to the feedstocks used in the unit, which were: clear water, sand-water slurry, sludge, fines-water slurry and sand-fines-water slurry. The rheological investigations were divided into three classes: sludge, fines-water slurry and synthetic fines-water slurry.

A listing of the data available can be seen in TABLE III-1, in which the series number and type of test are given.

The data reported in the tables in APPENDIX "F" are different from table to table and are based on different measured variables. A short discussion of each series is included in APPENDIX "A", which outlines the variables measured, the calculation procedures and the relative accuracy of results. A summary of the calculation procedures is given in TABLES A - 2 to -11. The constants used are listed in TABLE A-1.

3.3 Accuracy of Data:

The instrumentation and experimental equipment were altered as the program proceeded. This resulted in obtaining data with somewhat different orders of accuracy. The log included in APPENDIX "A" notes instrumentation difficulties and comments on the accuracy of some of the data. A more important aspect of the log is that of giving the chronological sequence of testing so that it is possible to evaluate the relative accuracy of results. APPENDIX "B" contains a detailed

TABLE III-1

SERIES	FEEDSTOCK	TYPE of TEST	Data Table
1000 - 1099	Clear Water	1" Steel Pipeline	F-1
1100 - 1199	Clear Water	1" Aluminum Pipeline	F-2
1200 - 1299	Clear Water	Initial 2" Steel Pipeline	F-3
1300 - 1399	Clear Water	2" Aluminum Pipeline	F-4
1400 - 1499	Clear Water	Modified 2" Steel Pipeline	F-5
1600 - 1699	Clear Water	1% Slope Flume	F-6
1800 - 1899	Clear Water	3% Slope Flume	F-7
2000 - 2099	Sand-Water Slurry	1" Steel Pipeline	F-8
2100 - 2199	Sand-Water Slurry	1" Aluminum Pipeline	F-9
2200 - 2299	Sand-Water Slurry	Initial 2" Steel Pipeline	F-10
2300 - 2399	Sand-Water Slurry	2" Aluminum Pipeline	F-11
2800 - 2899	Sand-Water Slurry	3% Slope Flume	F-12
2900 - 2999	Sand-Water Slurry	4% Slope Flume	F-13
3200 - 3299	Sludge	Initial 2" Steel Pipeline	F-14
3600 - 3699	Sludge	1% Slope Flume	F-15
3700 - 3799	Sludge	2% Slope Flume	F-16
3800 - 3899	Sludge	3% Slope Flume	F-17
3900 - 3999	Sludge	4% Slope Flume	F-18
4200 - 4299	Fines-Water Slurry	Initial 2" Steel Pipeline	F-19
4700 - 4799	Fines-Water Slurry	2% Slope Flume	F-20
4900 - 4999	Fines-Water Slurry	4% Slope Flume	F-21
5400 - 5499	Fines-Sand-Water Slurry	Modified 2" Steel Pipeline	F-22
5700 - 5799	Fines-Sand-Water Slurry	2% Slope Flume	F-23
32000 - 32999	Sludge	Rheological Properties	F-24
41000 - 41999	Synthetic Fines-Water Slurries	Rheological Properties	F-25
44000 - 44999	Fines-Water Slurry	Rheological Properties	F-26

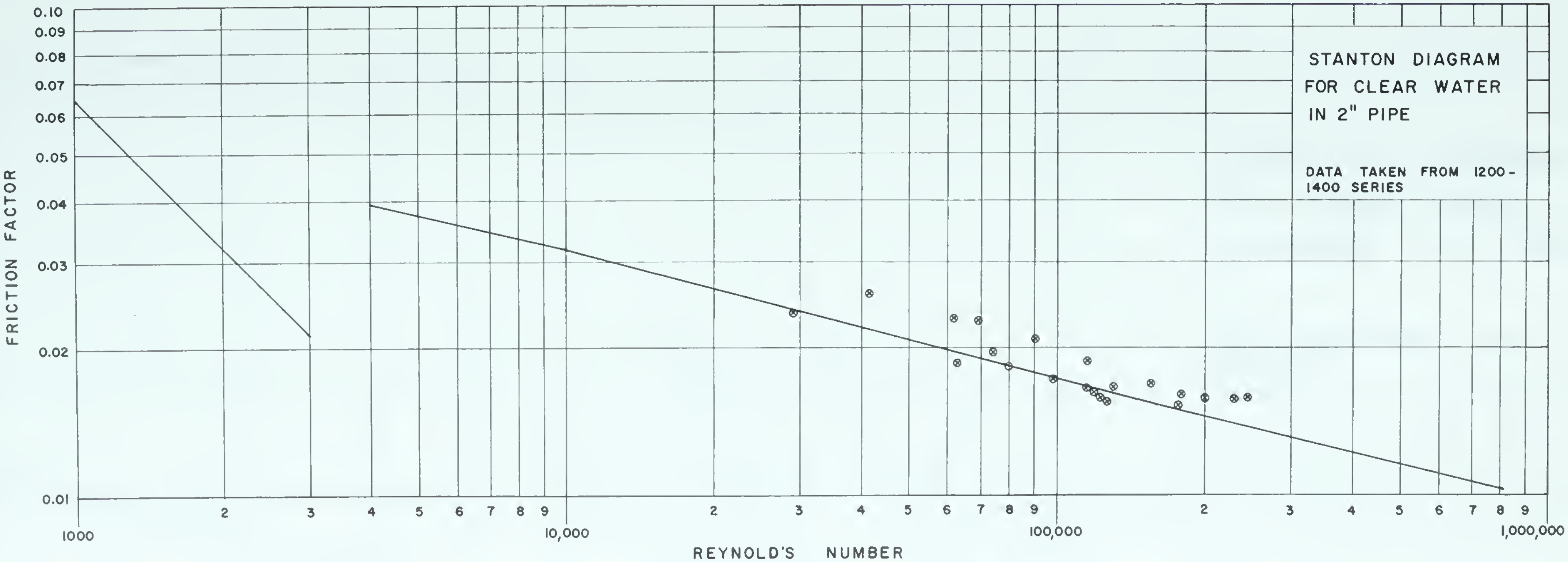
discussion on data and includes the statistical analyses of several series of tests which were carried out to determine the accuracy of measurements.

3.4 Clear Water in 2" Steel Pipeline:

The clear water data, as determined in the 2" steel pipeline for both the initial and modified test sections, have been plotted in FIG. III-1. This figure is a plot of the friction factor as defined by the Darcy-Weisbach equation vs. the Reynolds number in terms of the kinematic viscosity of water on log-log coordinates. The straight line on the left-hand side of the figure is a plot of the equation $f = \frac{64}{R_e}$, which shows the behaviour in the laminar region. The lower line on FIG. III-1 over the range of Reynolds numbers from 4,000 to 800,000 is a plot of the Blasius formula $f = \frac{0.316^{\frac{1}{4}}}{R_e}$. As can be seen on the figure, the data derived for clear water in the 2" pipeline fit this curve fairly well, with minimum scatter at higher Reynolds numbers.

3.5 Sand-Water Slurries in 2" Steel Pipeline:

The sand-water slurry data have been plotted on FIG. III-2 with the same reference lines as shown in FIG. III-1. The data as taken from TABLE F-10 were arbitrarily split into groups by ranges of concentration, and the curves were fitted by eye. It is apparent from this figure that the friction factor increases quite markedly with increasing sand concentration in the range of Reynolds numbers from


STANTON DIAGRAM
FOR CLEAR WATER
IN 2" PIPE
DATA TAKEN FROM 1200-1400 SERIES
FRICTION FACTOR
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
1000
10,000
100,000
1,000,000
REYNOLD'S NUMBER

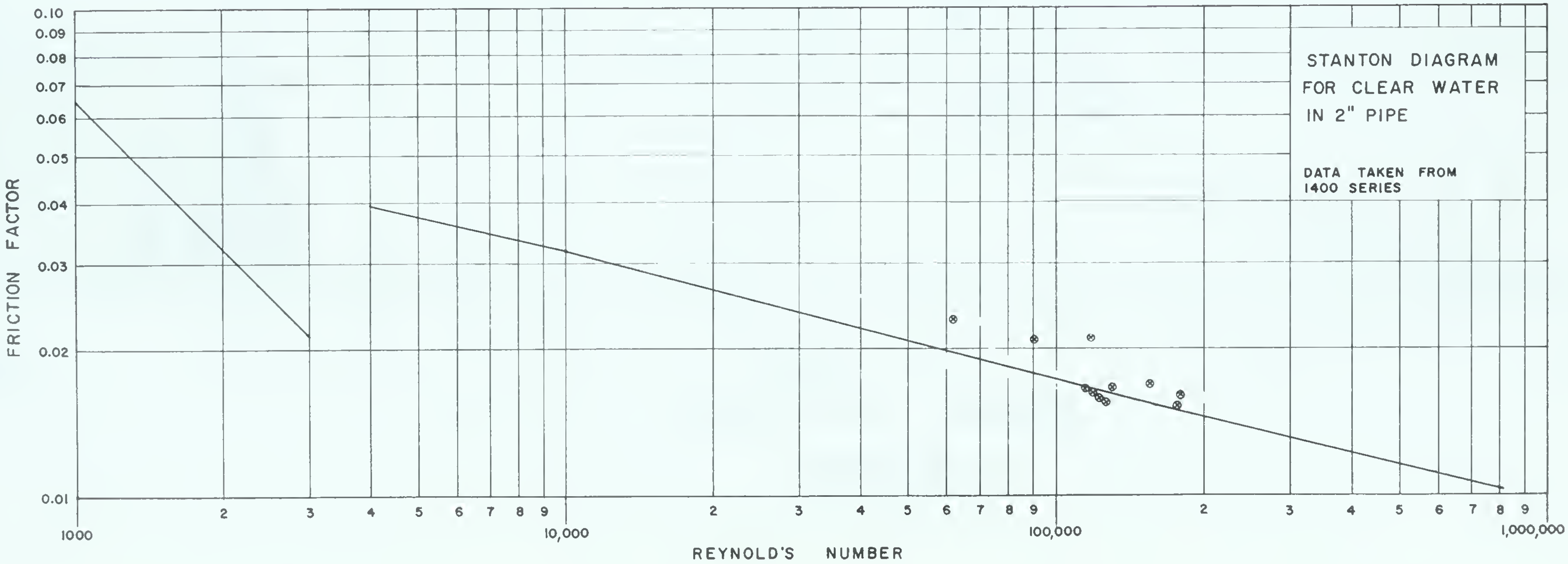
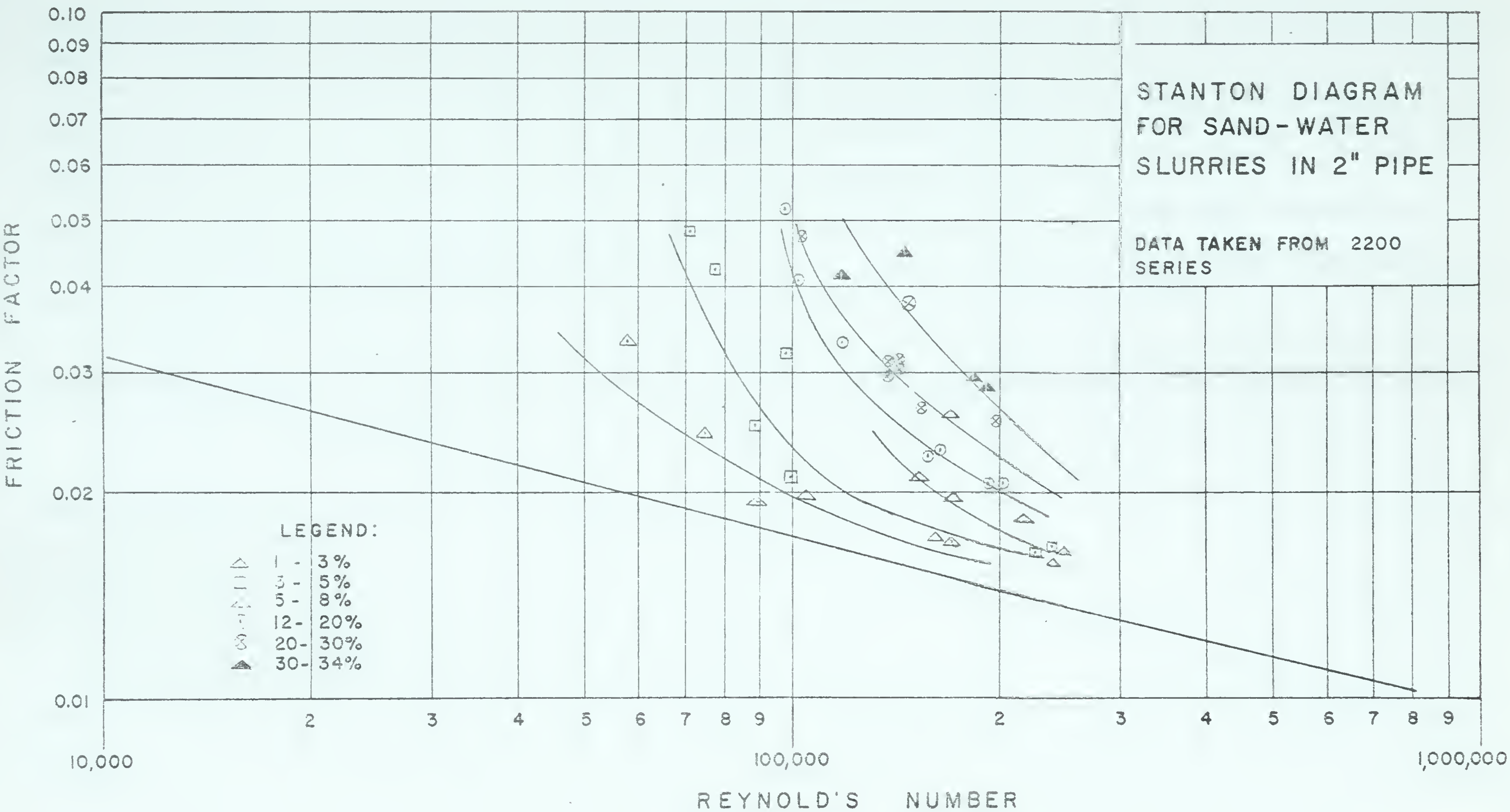

STANTON DIAGRAM
FOR CLEAR WATER
IN 2" PIPE
DATA TAKEN FROM 1400 SERIES
FRICTION FACTOR
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
1000
10,000
100,000
1,000,000
REYNOLD'S NUMBER

FIGURE III – I



STANTON DIAGRAM FOR SAND-WATER SLURRIES IN 2" PIPE
DATA TAKEN FROM 2200 SERIES
LEGEND:
1 - 3%
3 - 5%
5 - 8%
12- 20%
20- 30%
30- 34%
FRICTION FACTOR
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
10,000
2
3
4
5
6
7
8
9
100,000
1,000,000
REYNOLD'S NUMBER

FIGURE III - 2

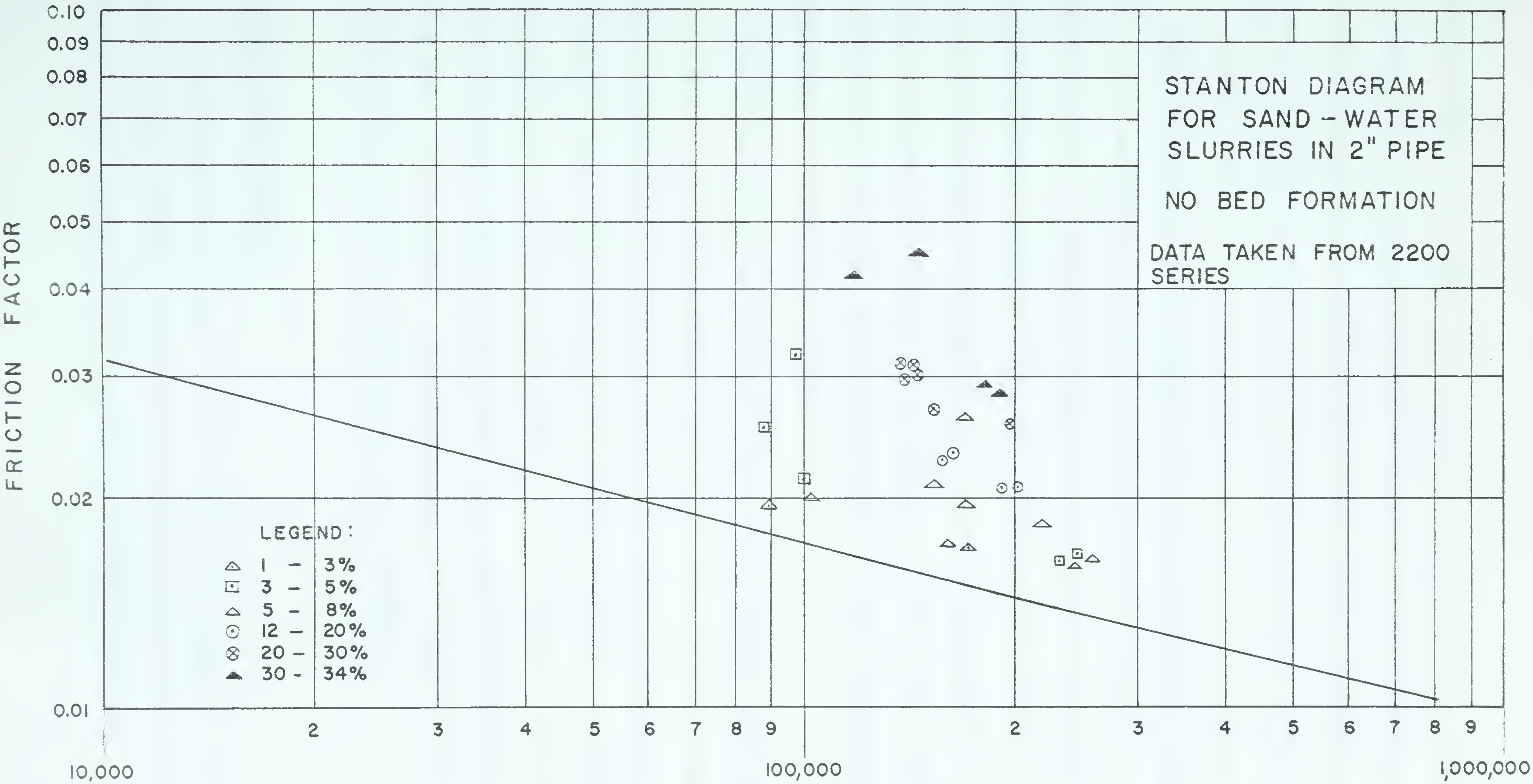

STANTON DIAGRAM
FOR SAND - WATER
SLURRIES IN 2" PIPE
NO BED FORMATION
DATA TAKEN FROM 2200
SERIES
LEGEND:
1 – 3%
3 – 5%
5 – 8%
12 – 20%
20 – 30%
30 - 34%
FRICTION FACTOR
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
REYNOLD'S NUMBER
10,000
2
3
4
5
6
7
8
9
100,000
2
3
4
5
6
7
8
9
1,000,000

FIGURE III-3

40,000 to 200,000. The figure also indicates that the curves converge on the Blasius line at higher Reynolds numbers. These results are quite consistent with those published by other workers, although the data are not usually shown in the form presented in FIGs. III-2 and III-3.

During some of the runs, a bed was present in the bottom of the pipe. When this phenomenon was observed in the transparent pipeline section, it was recorded as shown on TABLE F-10. FIG. III-3 is a similar plot to FIG. III-2, with the exception that the curves have been deleted and only those data for clean bed conditions are shown. As can be seen from this figure, this results in the data being plotted only in the range of Reynolds numbers from 100,000 to 300,000. The sharp divergences from the Blasius line shown in FIG. III-2 are associated with the formation of a bed in the pipeline.

When a bed is present in the pipeline, the Reynolds number as calculated and reported in TABLE F-10 is incorrect. If, for example, the pipe were half-full of sand, the Reynolds number as reported is approximately four-fifths as large as it actually should be. In this case, the points showing the high friction factor would be moved significantly to the right of the plot and some of the curves would show a turning point. Unfortunately, no measurements were taken during the testing to determine the depth of the bed in the pipeline.

3.6 Rheological Investigation:

A rheological study was carried out on three types of slurries: sludges, synthesized fines-water slurries and samples taken from the fines-water slurries used in the pipeline-flume test apparatus. The

synthetic slurries were made up to provide a range of concentrations of slurries which had not been obtained in sampling. The testing was directed toward developing some measure of consistency of the homogeneous fluid phase of the two- and three-component mixtures used in pipe-flume experiments.

A detailed description of the viscometer calibration and data processing is given in APPENDIX "C". The data can be found in TABLES F-24/26. One complete set of data (Run 41018) has been analysed to demonstrate the rheological properties of the slurries.

A plot of log Θ vs. log N can be seen on FIG. III-4, for which the points were fitted by eye with a straight line and the slope measured on the graph. An arithmetic plot of τ vs. $\frac{du}{dr}$ for Run 41018 is shown on FIG. III-5. The linear fit above 300 $sec.^{-1}$ was extrapolated to give an ordinate intercept. This plot can be compared to the classification charts presented by Govier (1962), which are included herein as FIG. III-6. The same type of plot has been prepared for several other slurries over a range of concentrations, as shown in FIG. III-7.

After a study of the plots of FIG. III-5, FIG. III-7 and several others for the data collected during the viscometer investigation, it was thought that the rheological behaviour was best described by the Bingham Plastic model (Govier, 1960). The observations in the flume described in Section A.21 certainly confirm that a yield stress must be overcome before the slurry can move. The plots shown in FIG. III-7 indicate that the yield stress increases with concentration, which is quite consistent with the observations reported by the author (Ansley, 1962).

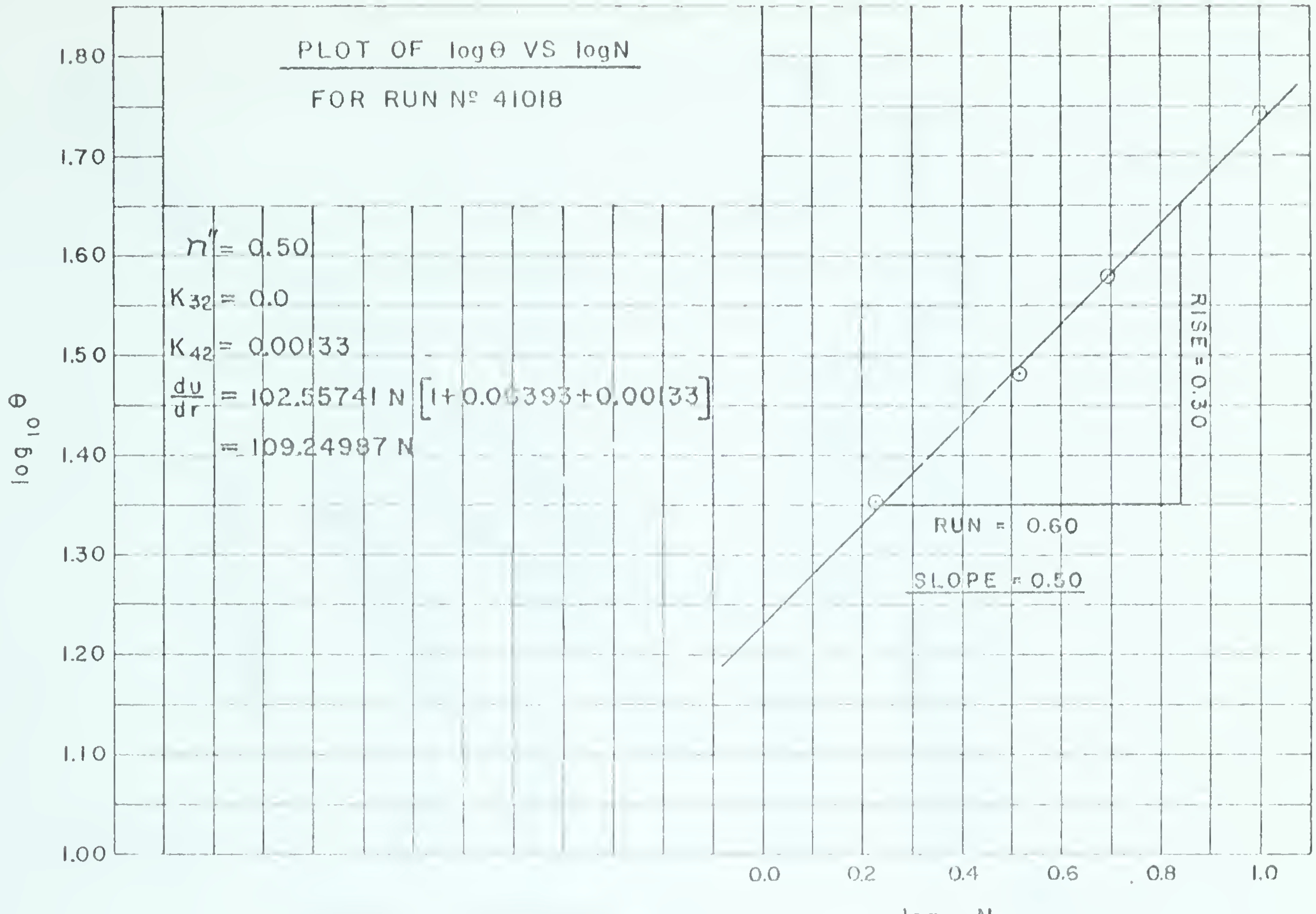


FIGURE III - 4

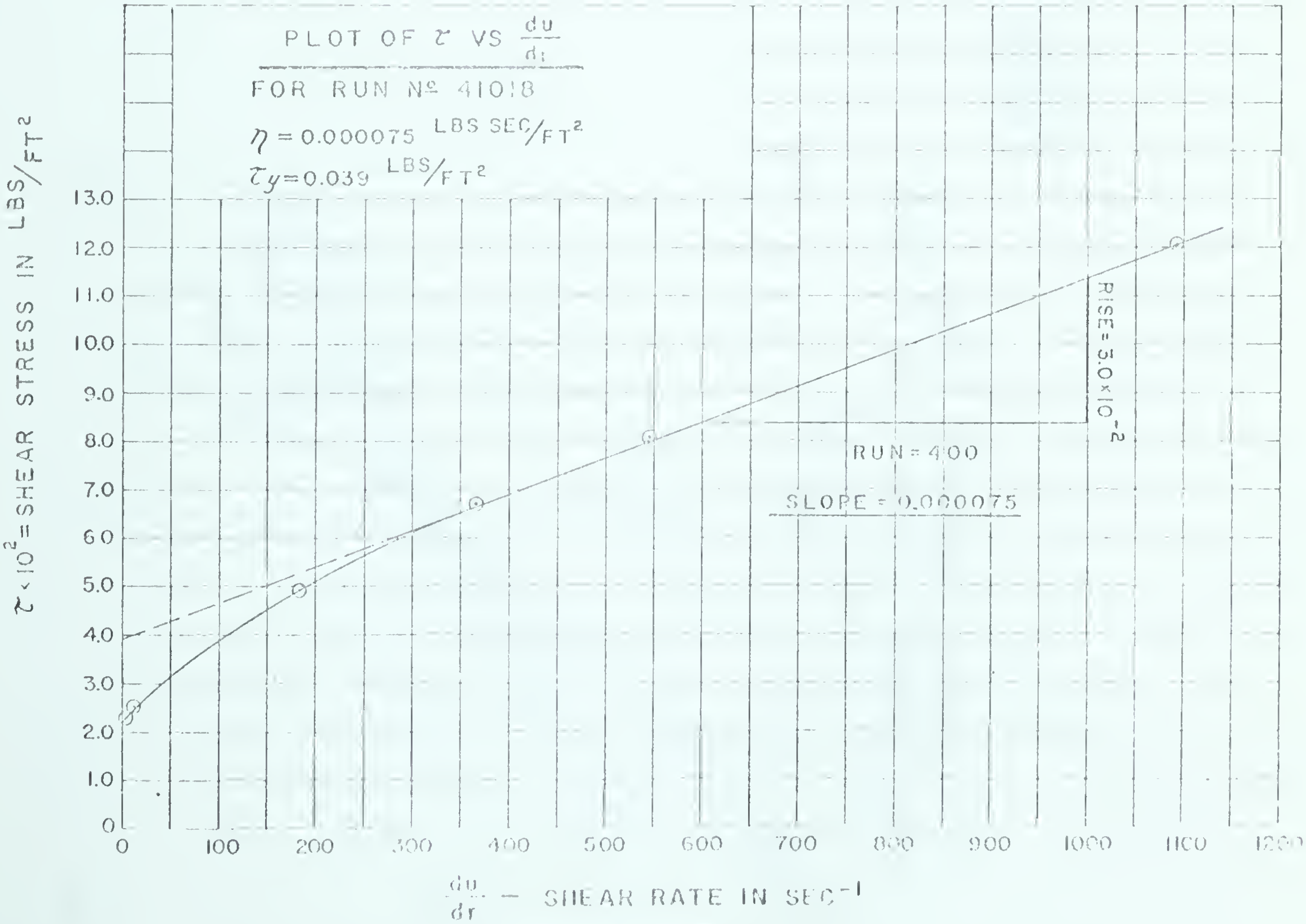
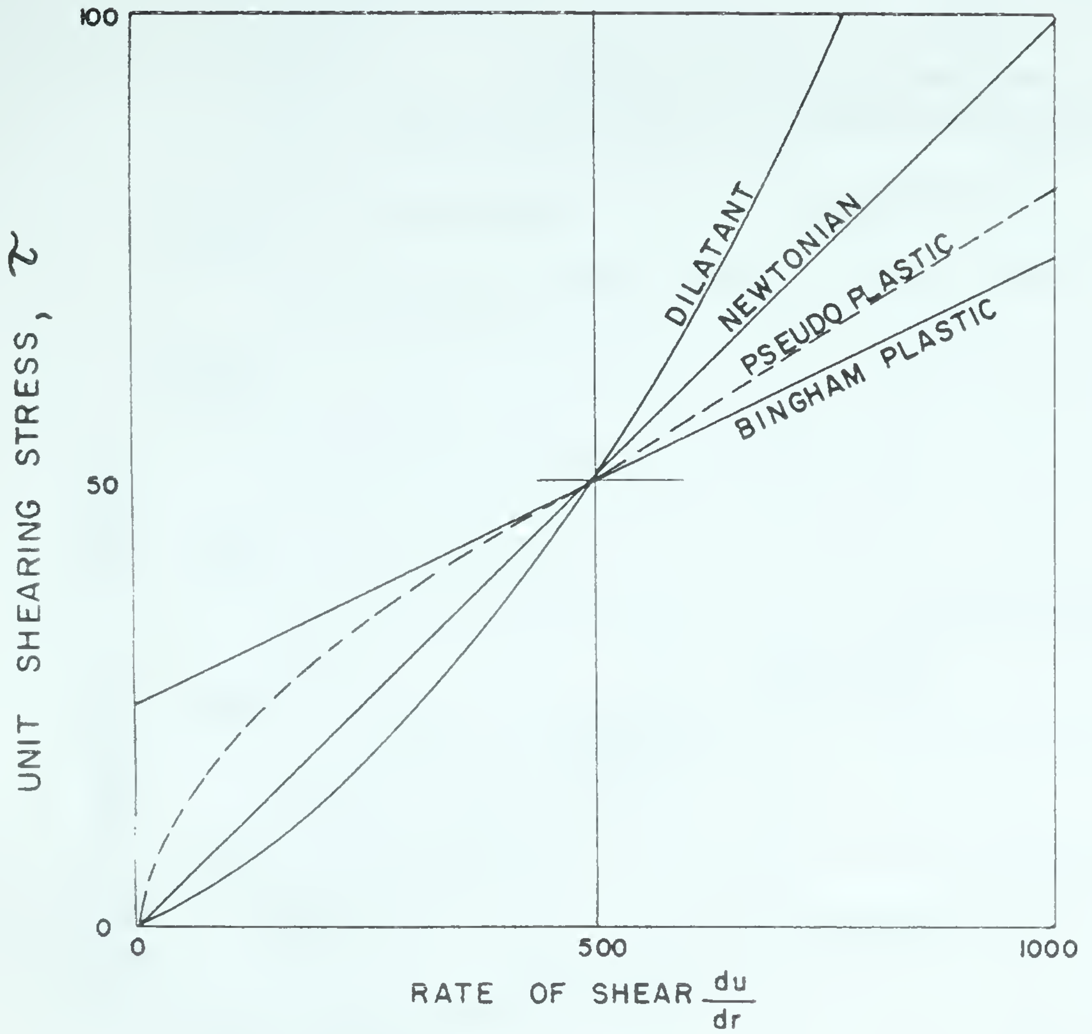
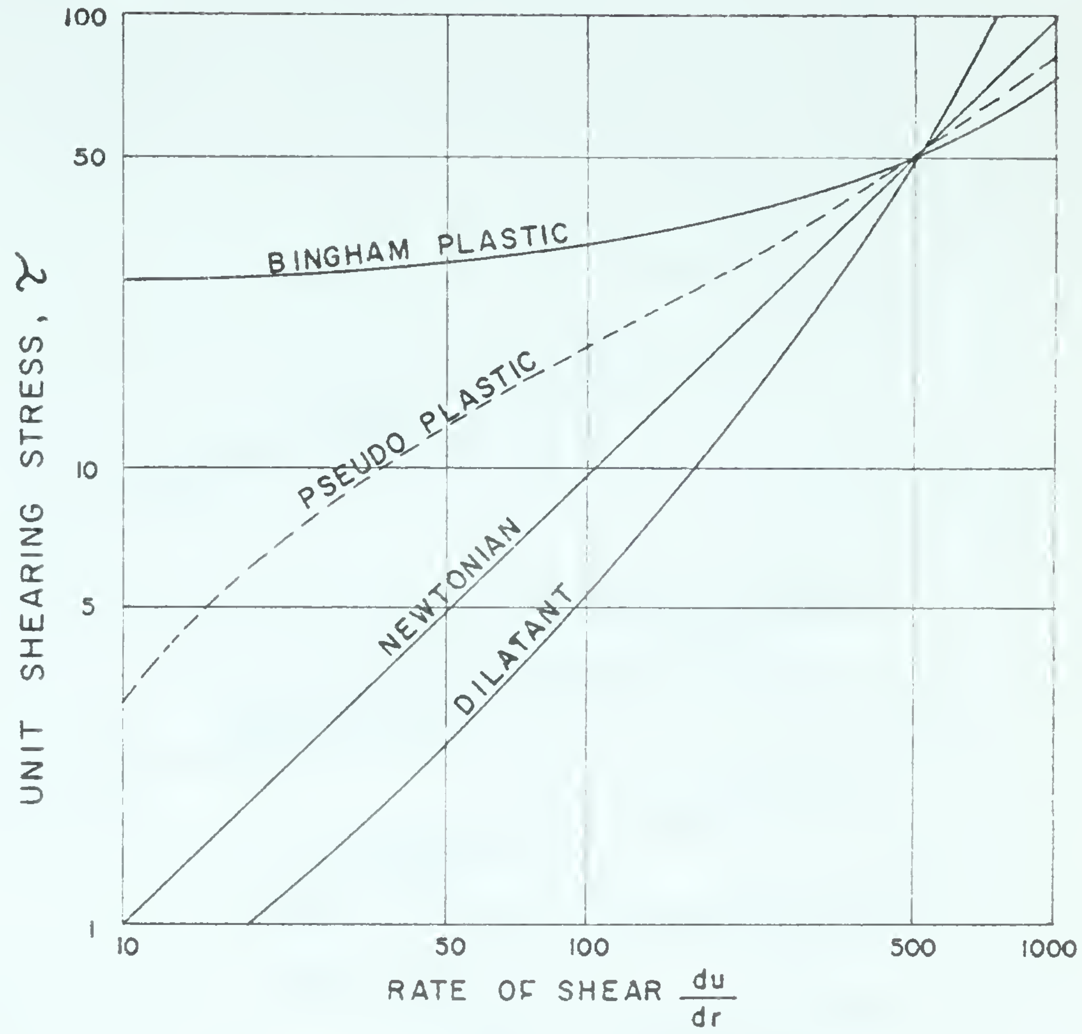


FIGURE III - 5



UNIT SHEARING STRESS – RATE OF SHEAR RELATIONSHIPS (ARITHMETIC PLOT).



UNIT SHEARING STRESS — RATE OF SHEAR RELATIONSHIPS (LOGARITHMIC PLOT).

FIGURE III – 6
(AFTER GOVIER)

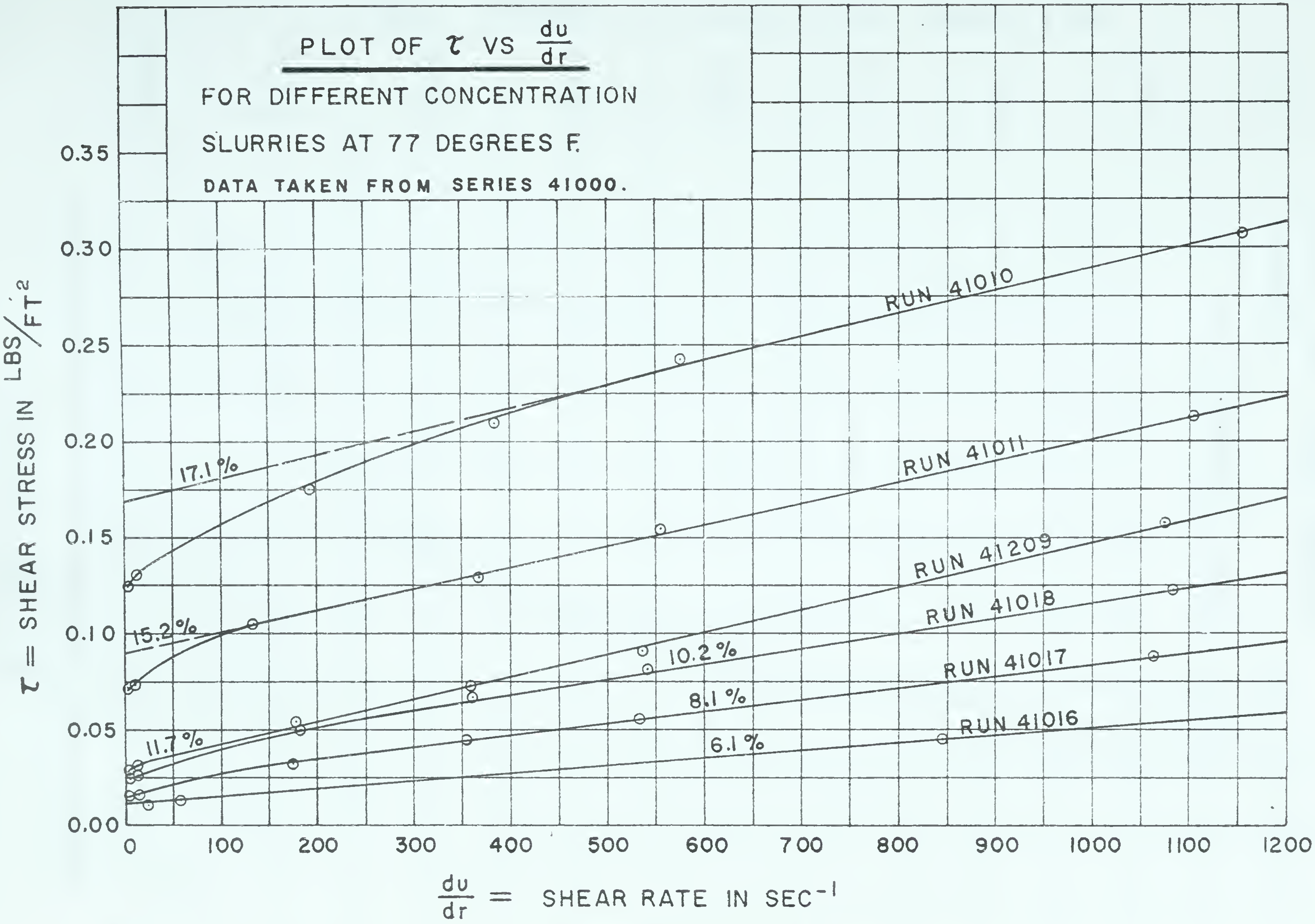

PLOT OF τ VS $\frac{du}{dr}$
FOR DIFFERENT CONCENTRATION
SLURRIES AT 77 DEGREES F.
DATA TAKEN FROM SERIES 41000.
RUN 41010
RUN 41011
RUN 41209
RUN 41018
RUN 41017
RUN 41016
17.1 %
15.2 %
11.7 %
10.2 %
8.1 %
6.1 %
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
τ = SHEAR STRESS IN LBS/FT²
$\frac{du}{dr}$ = SHEAR RATE IN SEC⁻¹

FIGURE III - 7

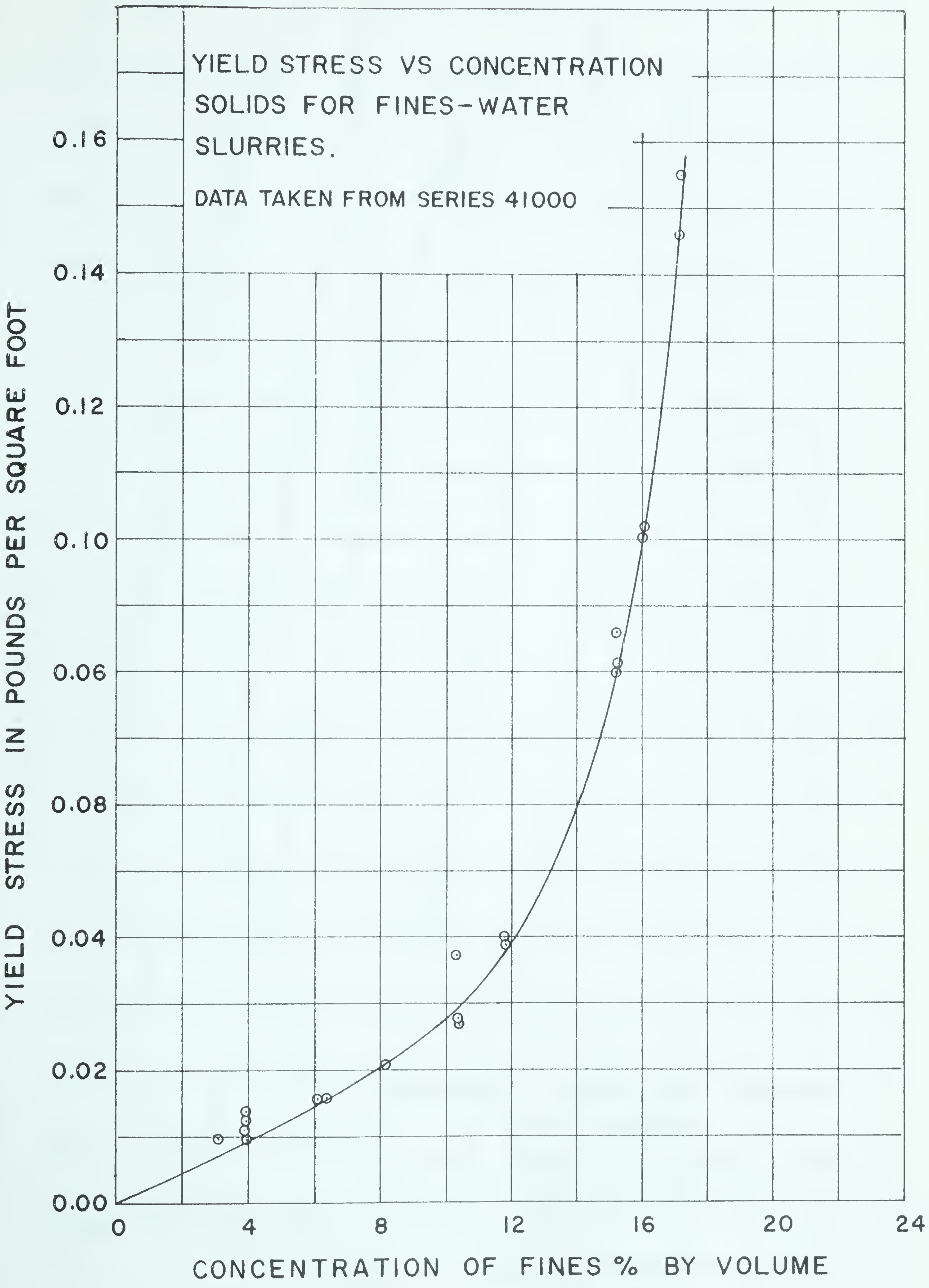

YIELD STRESS VS CONCENTRATION
SOLIDS FOR FINES-WATER
SLURRIES.
DATA TAKEN FROM SERIES 41000
0.16
0.14
0.12
0.10
0.06
0.08
0.04
0.02
0.00
YIELD STRESS IN POUNDS PER SQUARE FOOT
0
4
8
12
16
20
24
CONCENTRATION OF FINES % BY VOLUME

FIGURE III — 8

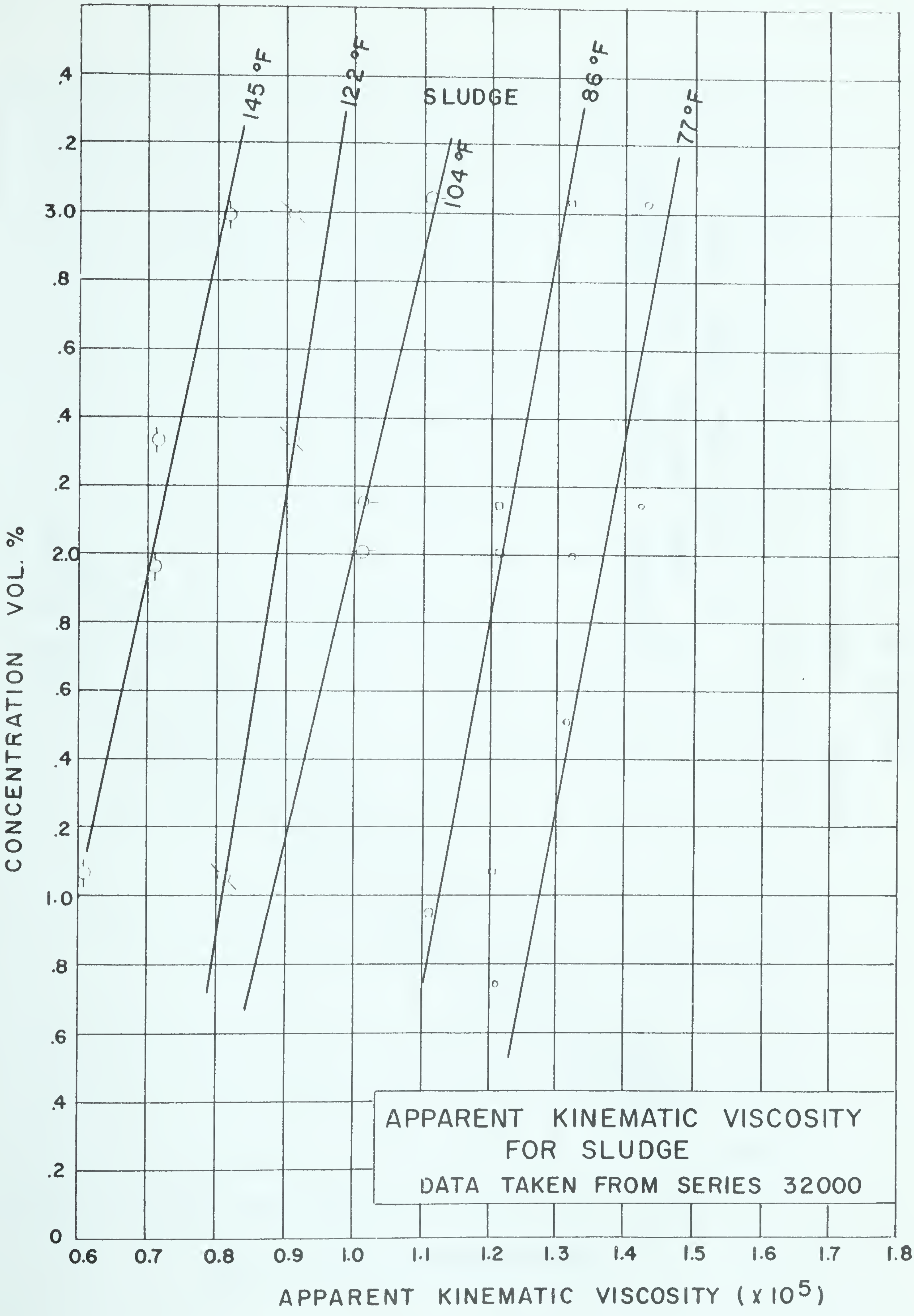

SLUDGE
145 °F
122 °F
104 °F
86 °F
77 °F
.4
.2
3.0
.8
.6
.4
.2
2.0
.8
.6
.4
.2
1.0
.8
.6
.4
.2
0
CONCENTRATION VOL. %
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
APPARENT KINEMATIC VISCOSITY (x 10⁵)
APPARENT KINEMATIC VISCOSITY
FOR SLUDGE
DATA TAKEN FROM SERIES 32000

FIGURE III - 9

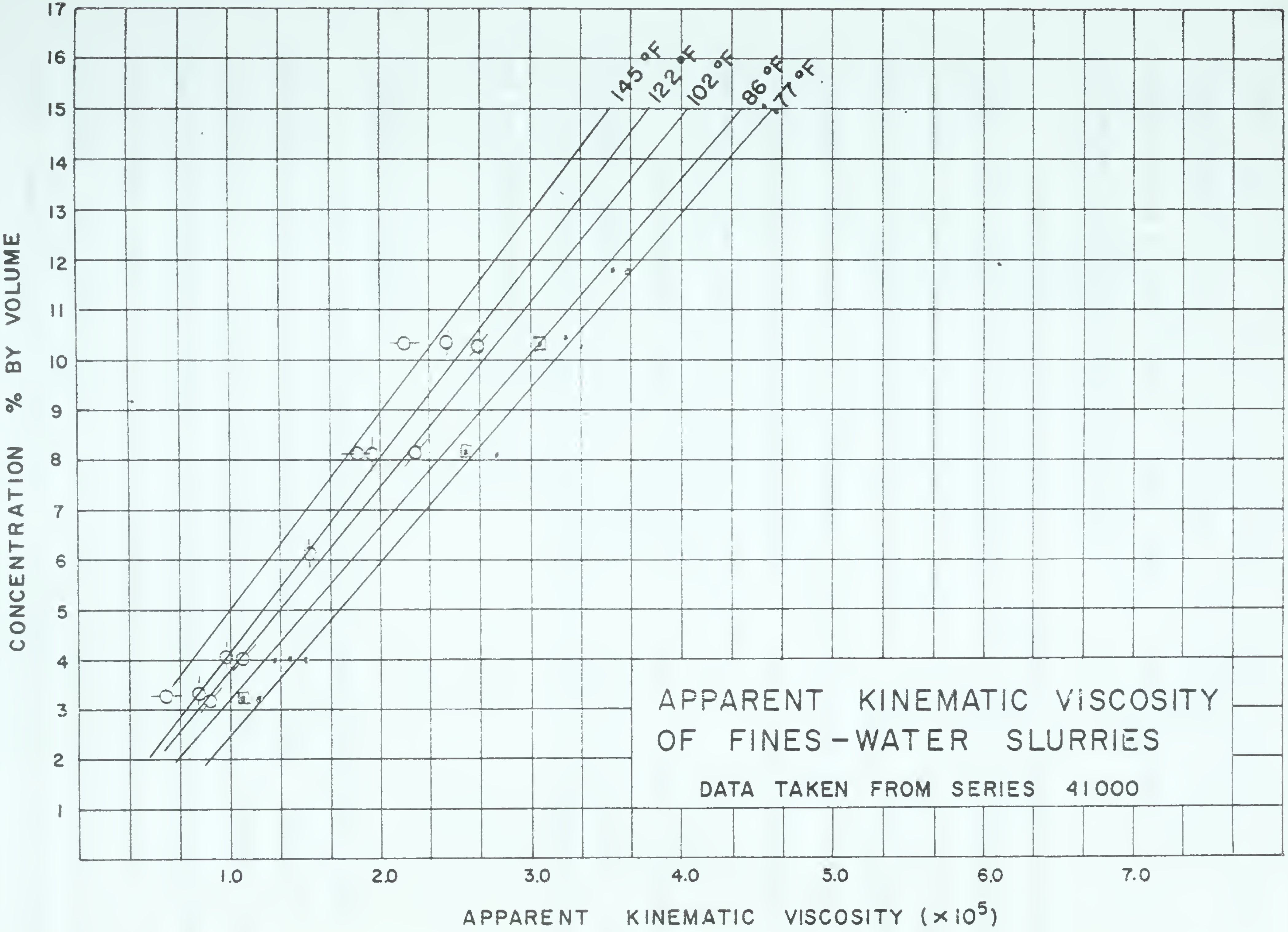


FIGURE III - 10

FIG. III-8 shows a plot of yield stress vs. concentration for the synthetic fines-water slurry which demonstrates this increase of yield stress with increase of concentration. The increase in height of surge waves in the flume was also noted to be associated with an increase in concentration of the fines.

Linear plots of concentration vs. apparent kinematic viscosity (FIGs. III-9 and III-10) have been prepared for sludge and fines-water slurries. The apparent kinematic viscosity is the coefficient of rigidity for the Bingham Plastic divided by the mass density. Temperature is shown on the plots as a parameter. The plots were fitted by eye and were used to interpolate the apparent kinematic viscosity values included in the data tables listed in TABLE III-1.

The apparent kinematic viscosity has been used in calculating Reynolds numbers for both two- and three-component mixtures. To avoid any confusion, this non-dimensional number is designated herein as the Bingham-Reynolds number.

3.7 Sludge in 2" Pipeline:

A plot of the Stanton diagram for the sludge in terms of the apparent kinematic viscosity can be seen in FIG. III-11. The data cluster fairly well about the Blasius line at a Bingham-Reynolds number of approximately 100,000. It is interesting to note that the friction factor drops quite noticeably for concentrations in the range of 0.90 to 2.0%. This phenomenon is consistent with the observations of Blench (1957), where he noted a decrease in friction factor for small concentrations of fines in earth canals with hydraulically smooth boundaries.

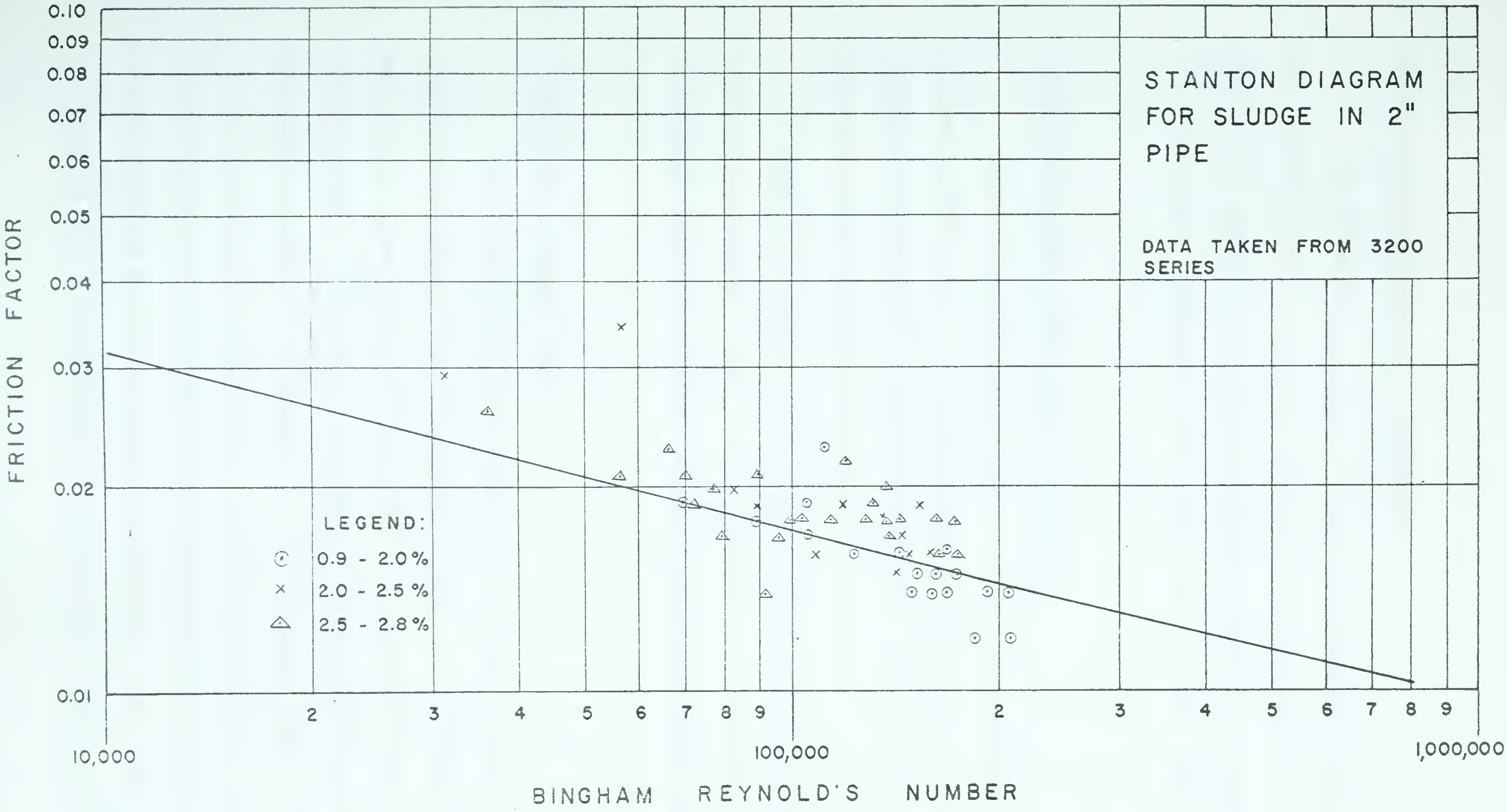


FIGURE III - 11

3.8 Fines-Water Slurries in 2" Pipeline:

The Stanton diagram, in terms of the Bingham-Reynolds number for fines-water slurries, can be seen in FIG. III-12. As in the case of the sludges, the low-concentration slurries correspond to a friction factor considerably lower than that for clear water.

3.9 Fines-Sand-Water Slurries in 2" Pipeline:

Some of the data for the three-component mixtures have been plotted on FIG. III-13. The remaining unplotted data correspond to a random concentration of either fines or sand and were therefore quite difficult to plot with concentrations as a parameter.

The data indicate that the presence of fines has an effect on a sand-water mixture. The low Bingham-Reynolds numbers are due to the high apparent viscosity of the homogeneous fines-water phase.

3.10 Clear Water in the Flume:

Two sets of data have been plotted on FIG. III-14 for clear water in the flume. The 1% slope data show a much higher friction factor than those for the 3% slope over a comparable range of Reynolds numbers. This may be partially explained after examining the operating log in APPENDIX "A". The 1% slope tests were carried out in the new wooden flume, whereas the 3% slope tests were performed after an extended testing period with sand-water slurries which smoothed the bed and sides of the flume. This effect can also be detected with a comparison of the hydraulic radii for the two series.

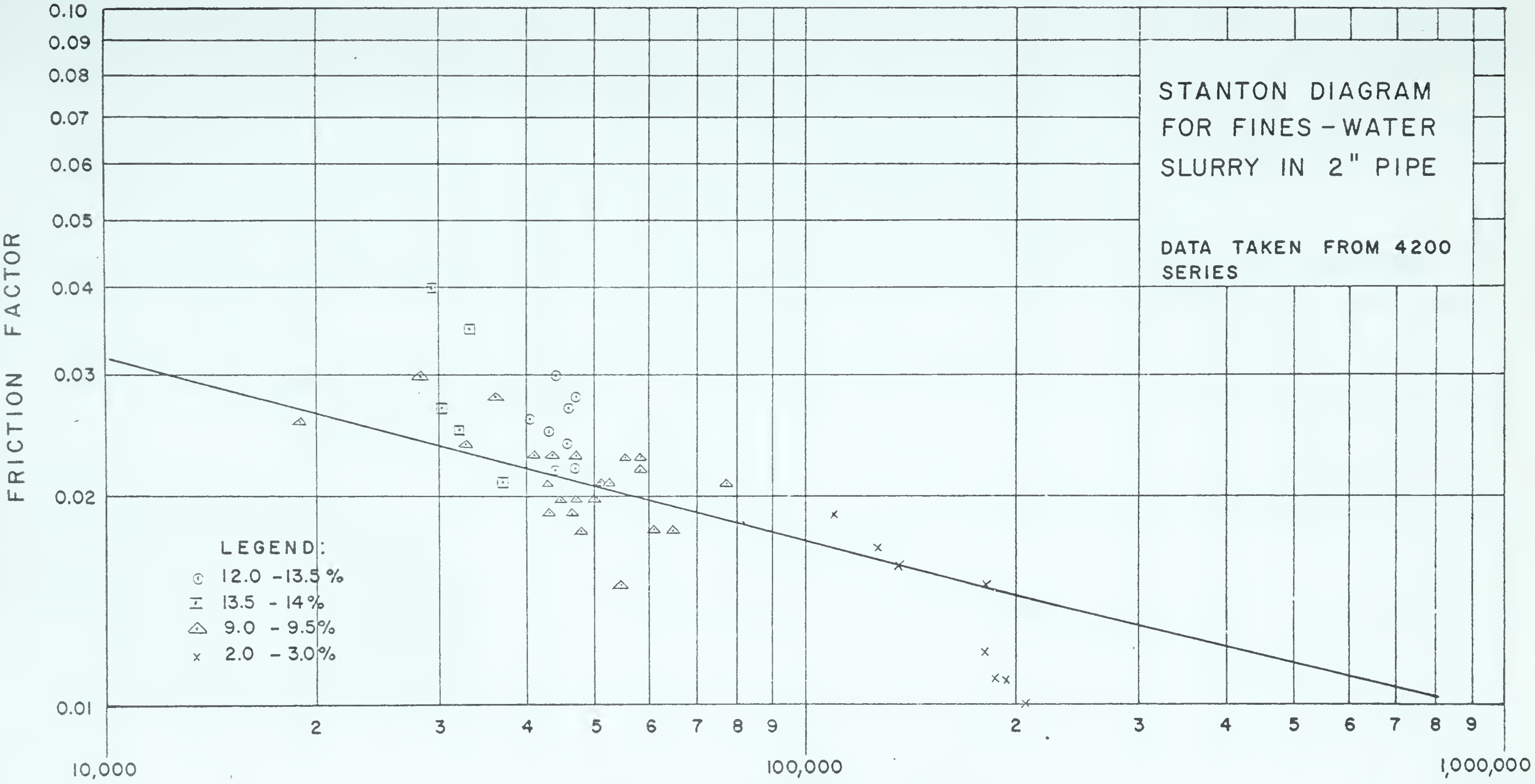


FIGURE III - 12

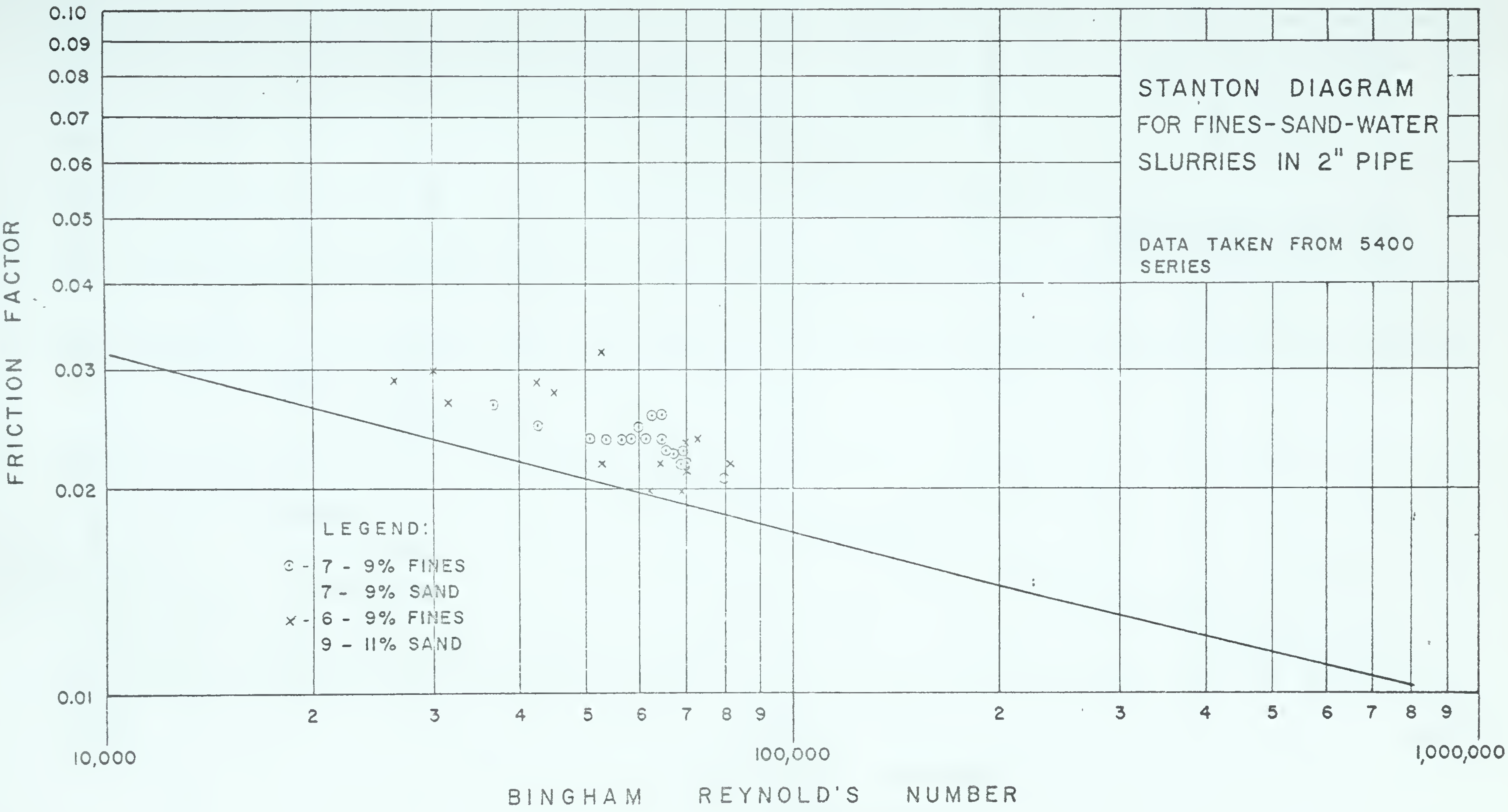


FIGURE III - 13

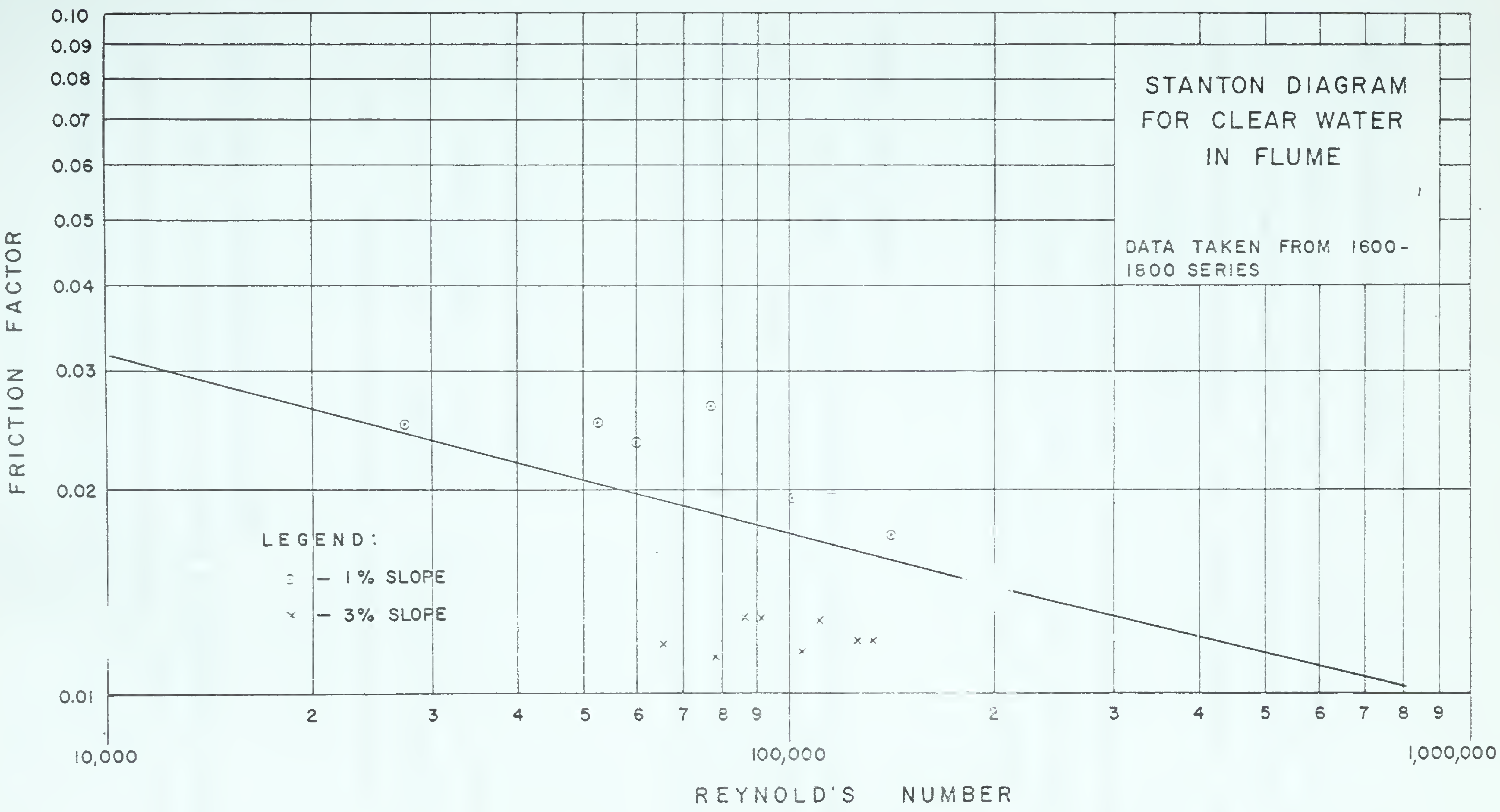


FIGURE III - 14

3.11 Sand-Water Slurries in the Flume:

A Stanton diagram for sand-water slurries can be seen in FIG. III-15. The classification for the plotted points is on the basis of both slope of flume and bed condition. The antidune formation is discussed in considerable detail in CHAPTER V.

The most significant feature of this series of tests is the extremely low concentration of solids in the slurries which could be transported without some form of deposited bed in the flume.

3.12 Sludge in the Flume:

The sludge data for the flume on a 2% slope has been plotted on FIG. III-16. The points, which are in terms of the Bingham-Reynolds number, are quite closely associated with the Blasius line, but do show some tendency to fall below the line for higher-concentration sludges.

3.13 Fines-Water Slurries in the Flume:

A Stanton diagram for the fines-water slurries in the flume at 2% slope can be seen on FIG. III-17. This figure markedly indicates the trend to fall below the Blasius line at high concentrations of fines.

3.14 Fines-Sand-Water Slurries in the Flume:

Two sets of data have been plotted on FIG. III-18 for fines-sand-water slurries in the flume at a 2% slope. These sets of data correspond to those plotted on FIG. III-13.

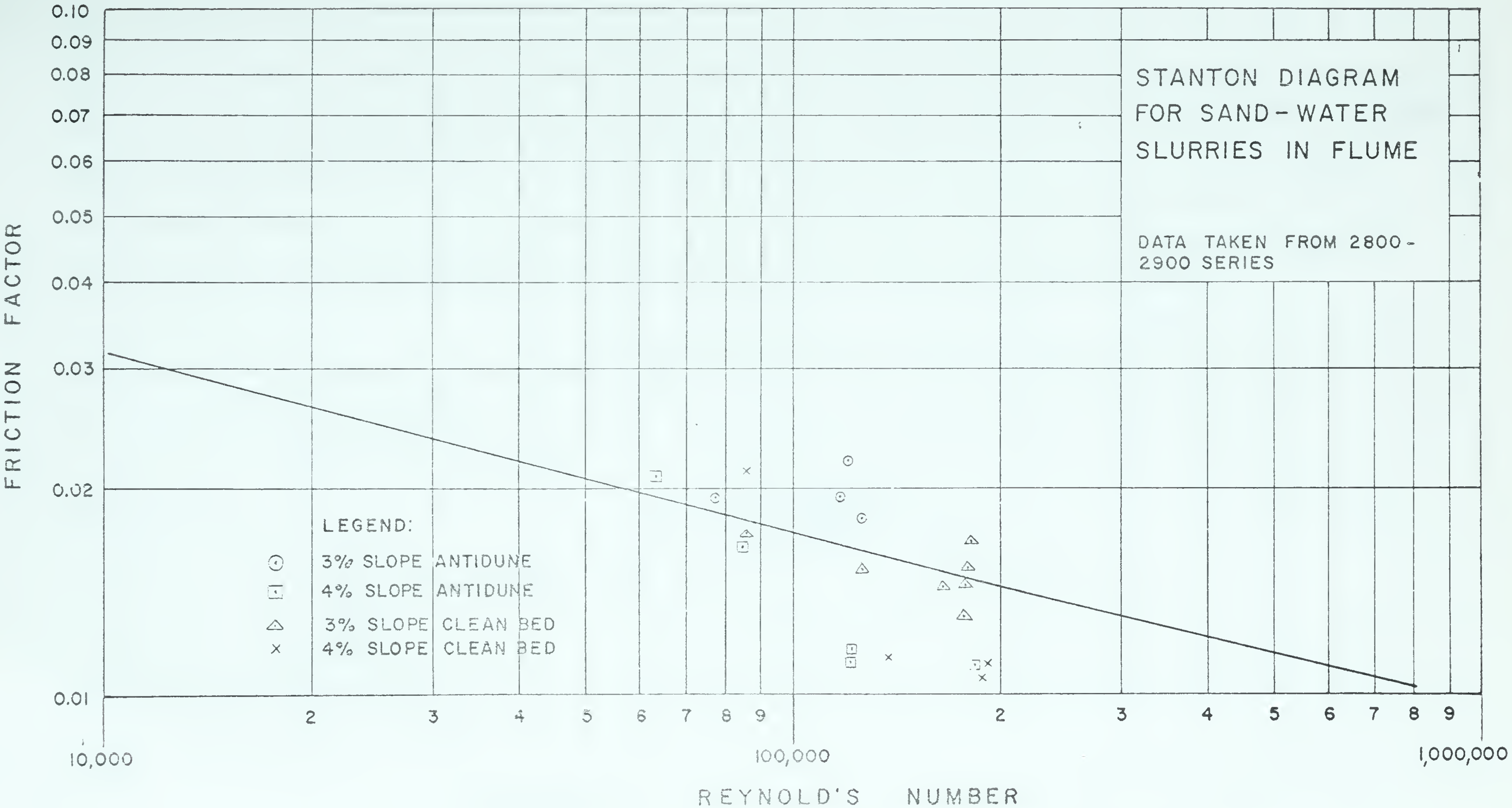


FIGURE III - 15

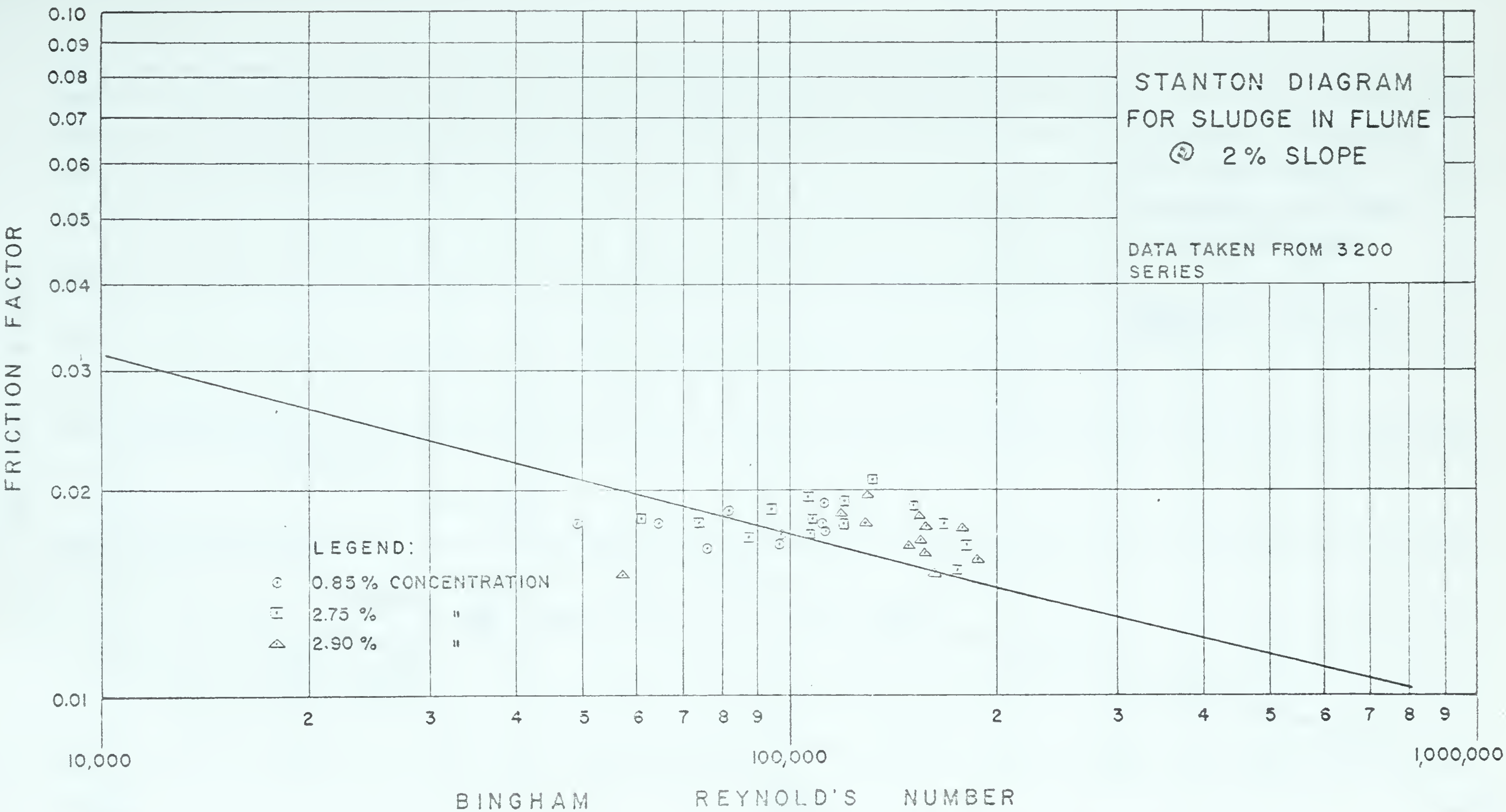


FIGURE III - 16

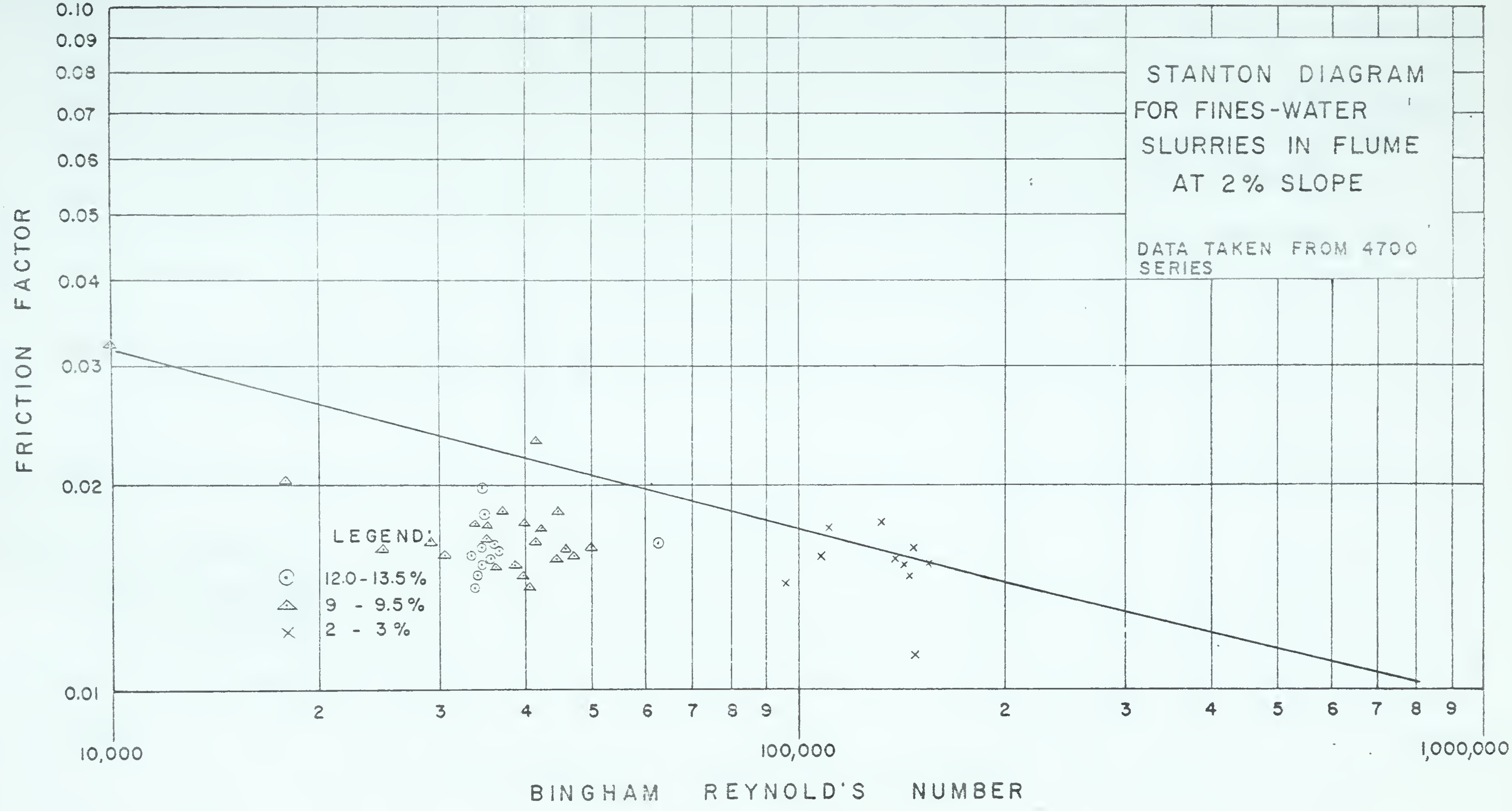


FIGURE III - 17

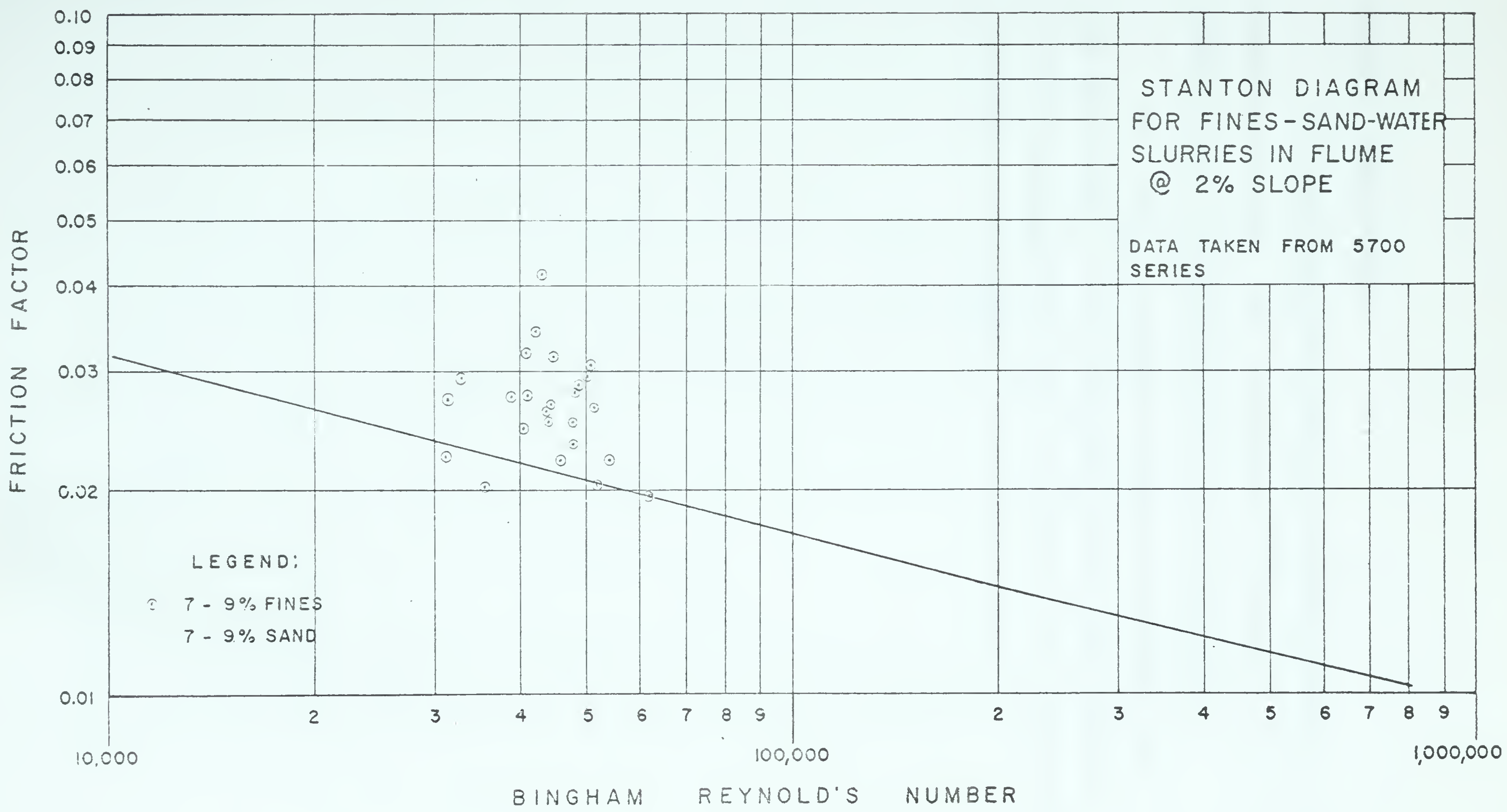
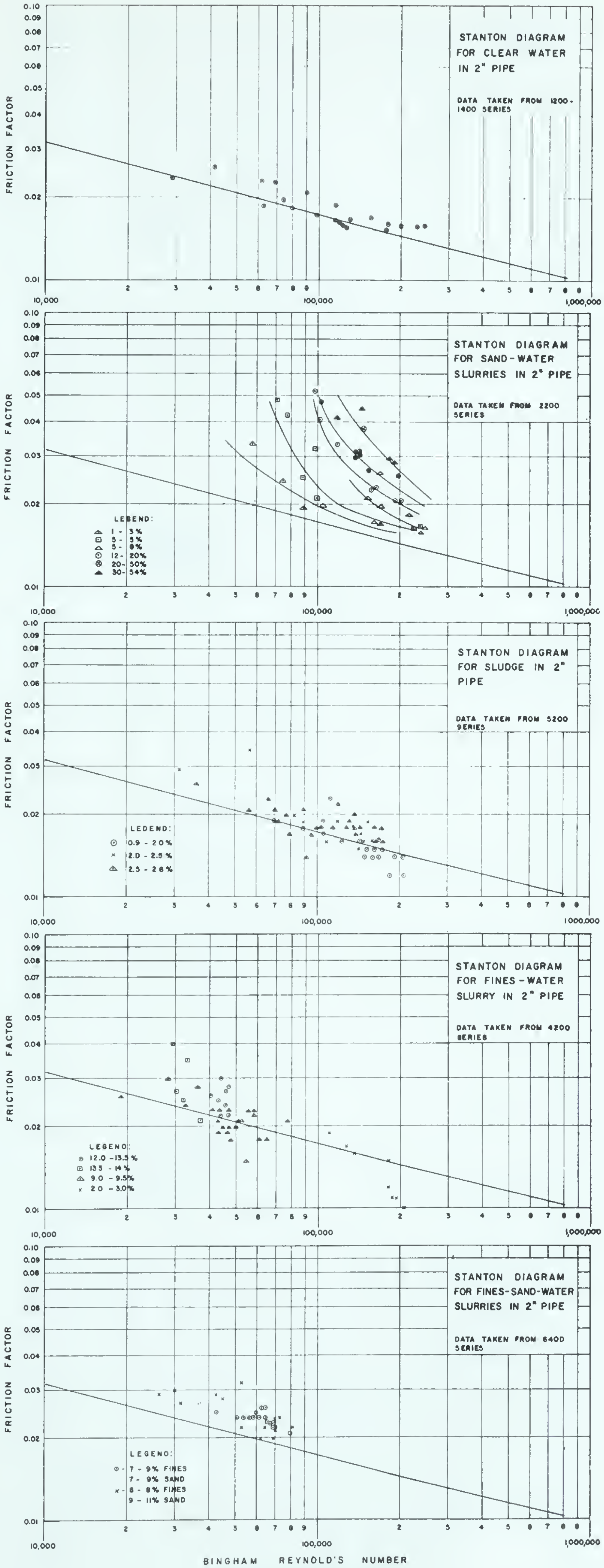


FIGURE III-18

3.15 Summary Plots of Data:

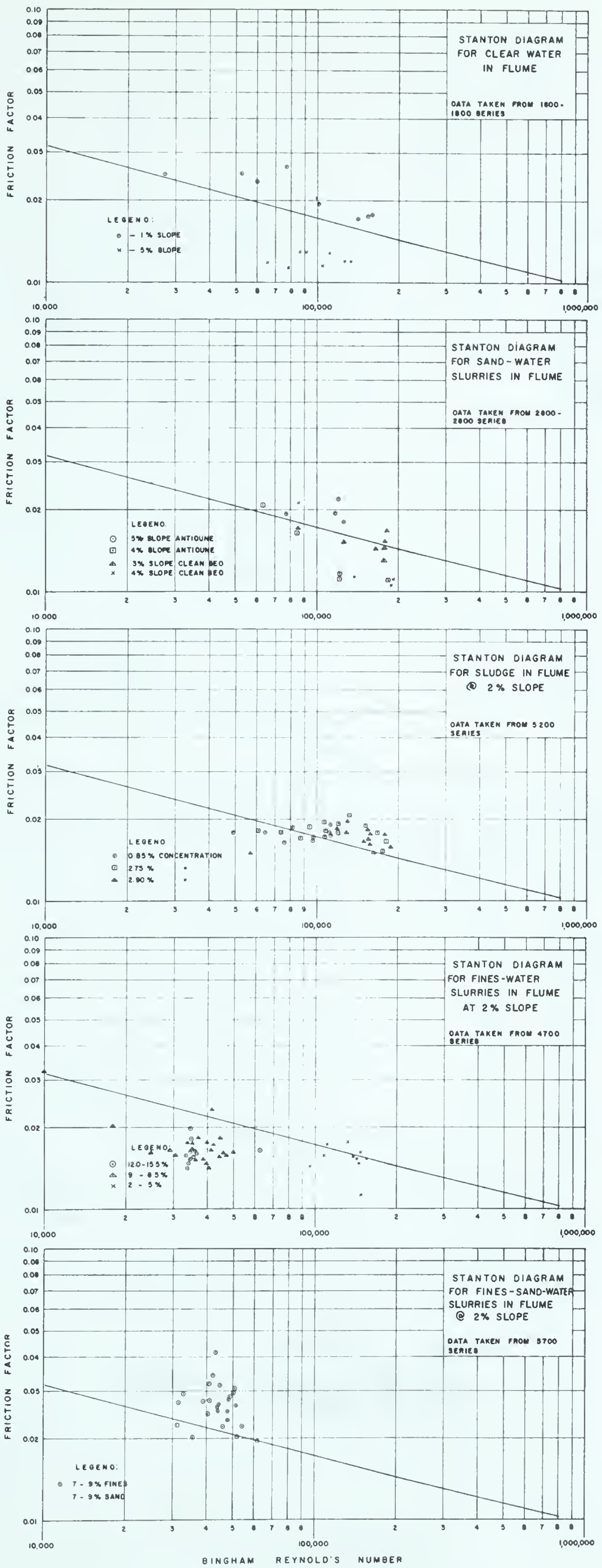
The Stanton diagrams have been grouped to facilitate a visual comparison of data. FIG. III-19 shows all the pipeline data on one page and FIG. III-20 duplicates this for the flume data.

FIG. III-21 is a summary of both pipe and flume data for water. FIG. III-22 shows a similar summary for sand-water slurries, FIG. III-23 for fines-sand-water slurries, FIG. III-24 for sludge and FIG. III-25 shows the same data for fines-water slurries.



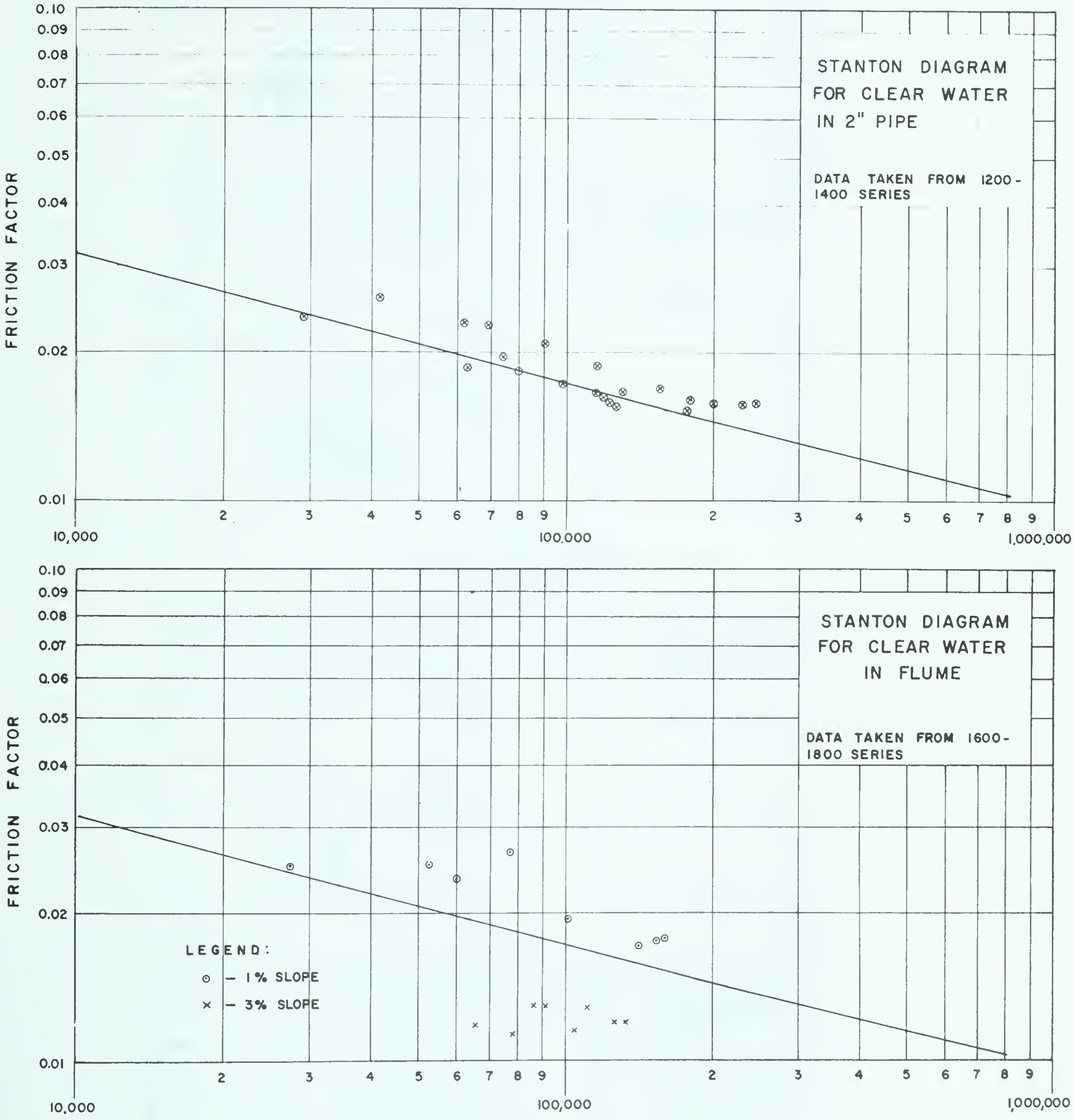
SUMMARY OF 2" PIPE DATA

FIGURE III-19



SUMMARY OF FLUME DATA

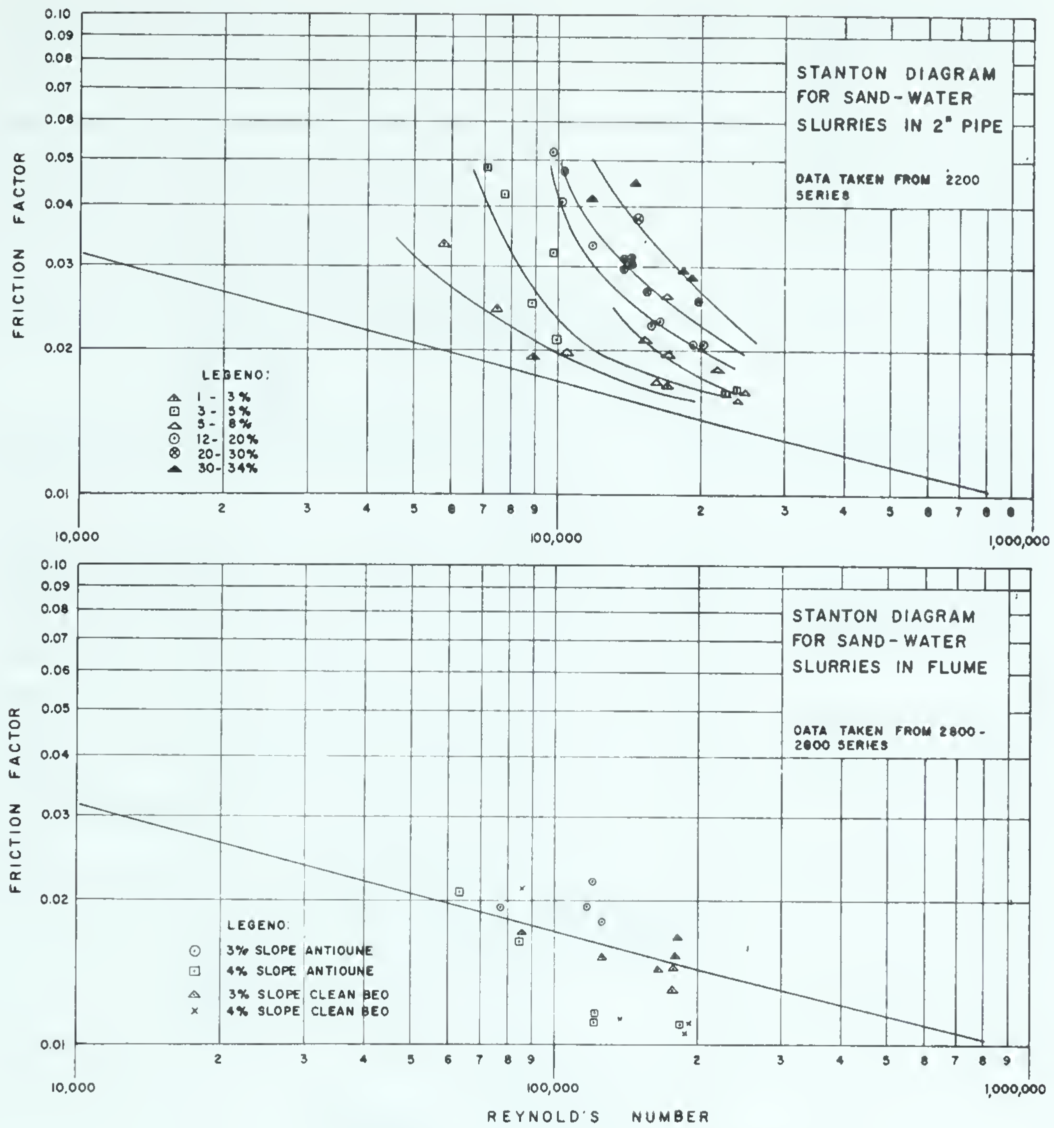
FIGURE III-20



REYNOLD'S NUMBER

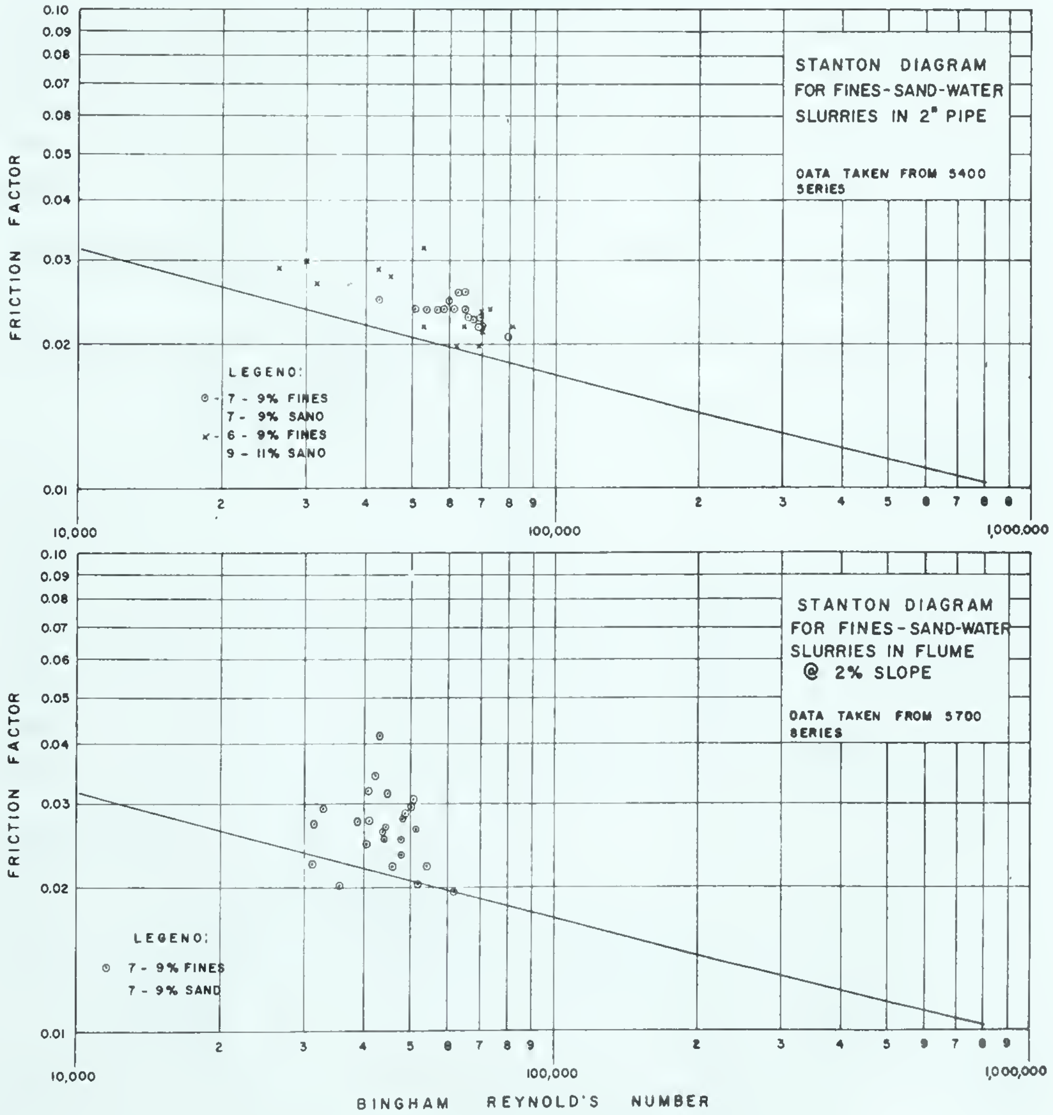
SUMMARY OF CLEAR WATER DATA

FIGURE III - 21



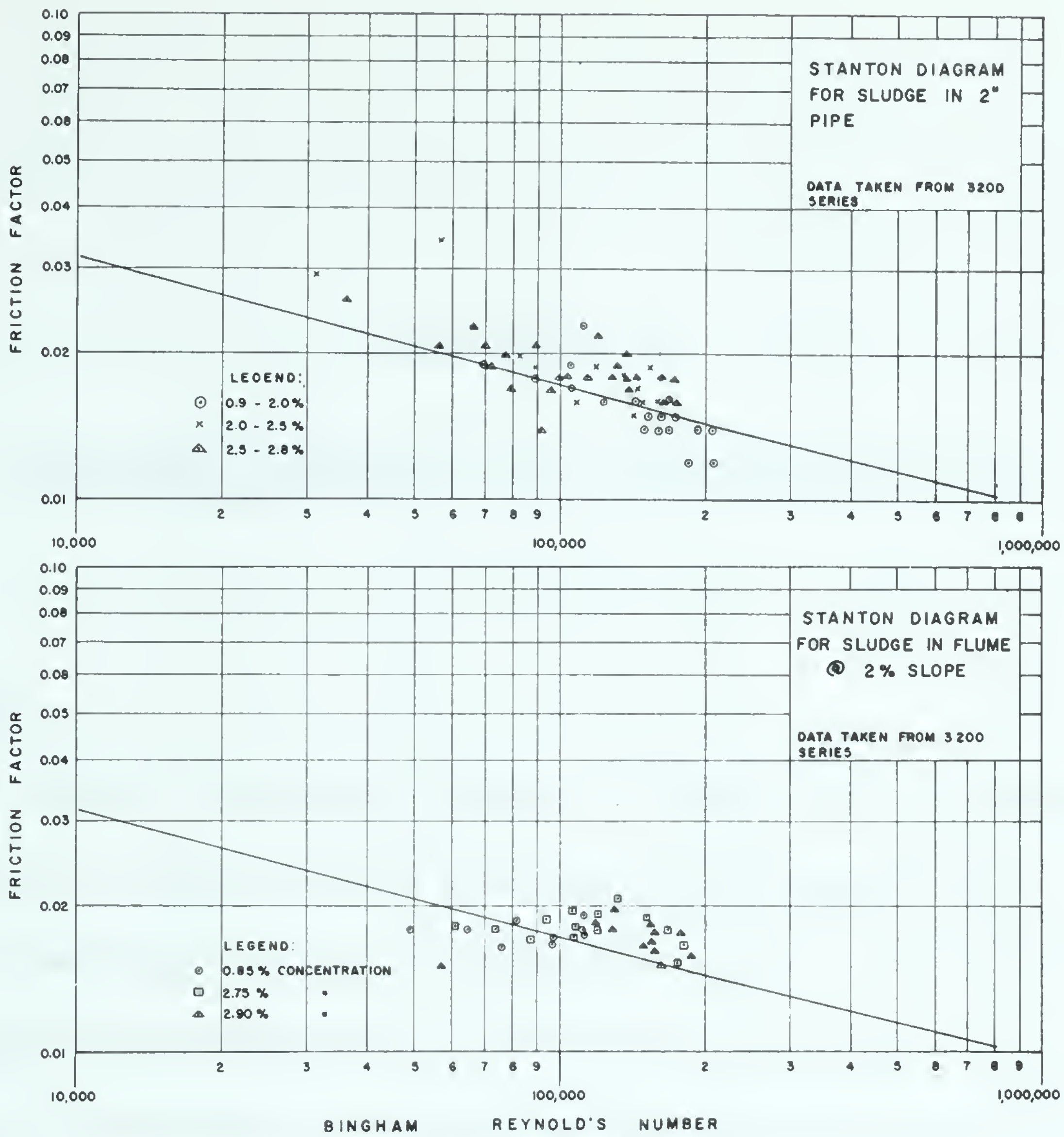
SUMMARY OF SAND-WATER SLURRY DATA

FIGURE III-22



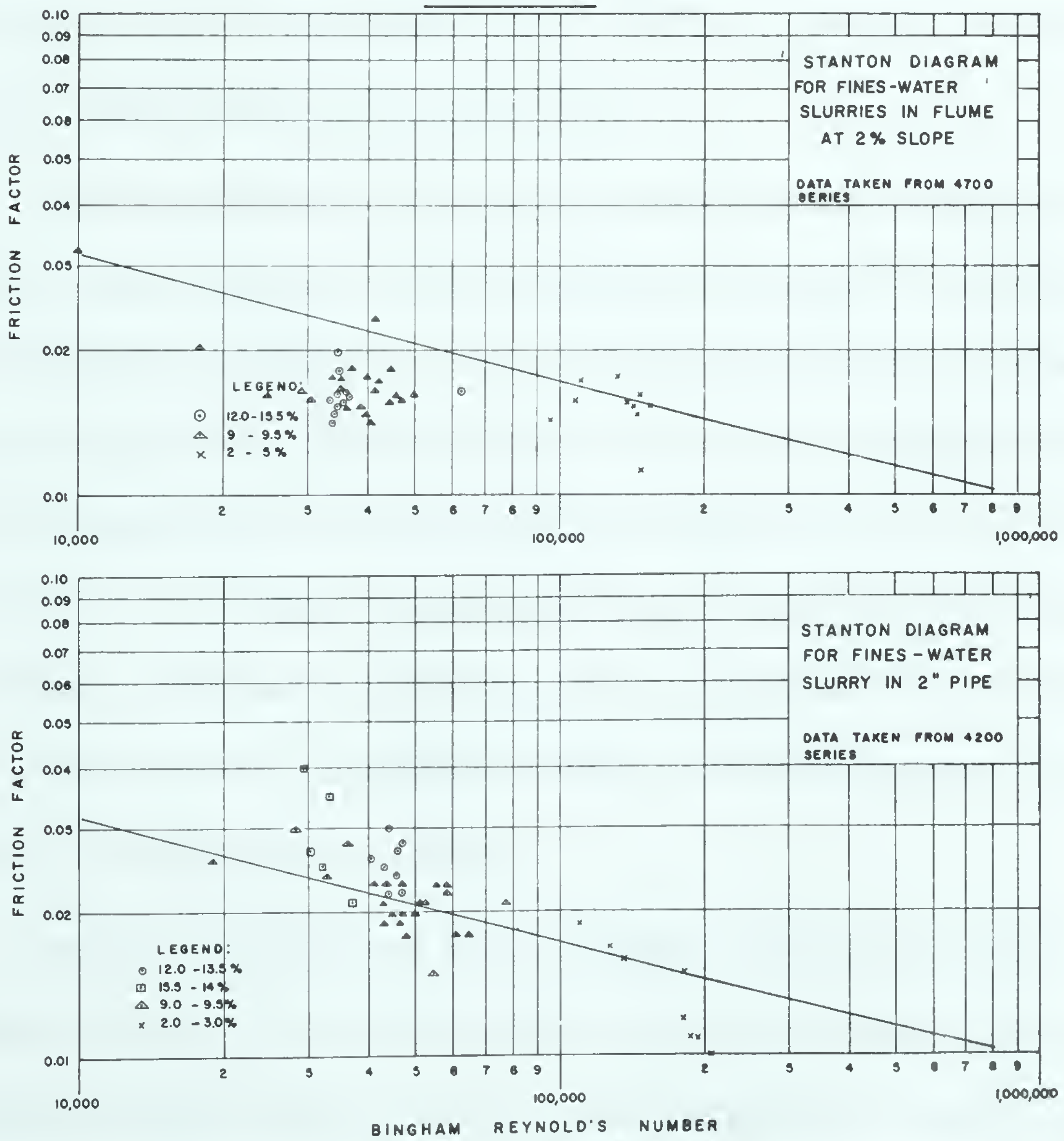
SUMMARY OF FINES-SAND-WATER SLURRY DATA

FIGURE III-23



SUMMARY OF SLUDGE DATA

FIGURE III - 24



SUMMARY OF FINES-WATER DATA

FIGURE III - 25

CHAPTER IV

PIPELINE TRANSPORT OF FLUIDIZED SOLIDS

4.1 General:

Virtually all data and theory of transport of fluidized solids published to date have been associated with pipeline flow. This chapter includes a fairly comprehensive review of published data. The information obtained at the University of Alberta and included herein is compared to the published correlations of other workers. A discussion of the validity of some of the supporting assumptions for these hypotheses is also included.

The observations of the physical phenomena taking place in fluidized solids transport have contributed greatly to the boundary conditions and assumptions made by the theoreticians. Since any theory or hypothesis must satisfy the boundary conditions and should be consistent with the physical behaviour, there is considerable merit in reviewing the publications of other experimenters. In particular, the early workers' observations are very pertinent in that they were not encumbered with preconceived theories or limited by accepted assumptions.

Despite the fact that experimental work on pipeline transport of fluidized solids has been carried on for over fifty years, there has been no unified theory which is acceptable to industry as a

whole. There are two definite schools of thought on the subject of large pipeline designs for fluidized solids systems. There are many who currently believe that it is a hopelessly inexact science requiring a complete, 100% scale pilot plant operation to gather the necessary design data. The diametrically opposite view is that of the theoreticians who, using the results of some hundreds of experiments, have formulated either empirical correlations or semi-theoretical predictions which could be used to design major works.

4.2 Brief Historical Review of Published Data:

It is generally conceded (Newitt et al, 1955) that Hazen and Hardy formulated the first investigation into hydraulic transport of fluidized solids in pipelines in 1906. In a discussion of Hazen and Hardy's paper, Blatch (1906) brought forth the first reliable data for sand-water slurries in small pipelines. All three workers felt that the basic problem was one of finding a method of predicting both the critical deposit velocity and the hydraulic gradient vs. mean velocity in the pipeline, on arithmetic coordinates as shown on FIGS. IV-1 and IV-2. The data of Series 1200 and 1400 for clear water in the 2" pipe have been plotted on FIG. IV-1. A regression analysis of twenty-four pieces of data yielded the equation -

$$i_w = 0.00226\ V^{1.8133} \quad \ldots\ldots\ldots\ldots\ldots \quad (4\text{-}1)$$

with a correlation coefficient of 0.992 between Log i_w and Log V. The regression technique and correlation coefficient calculation are detailed in APPENDIX "D". FIG. IV-2 shows this clear-water line, together with the sand-water slurry results of the 2200 Series.

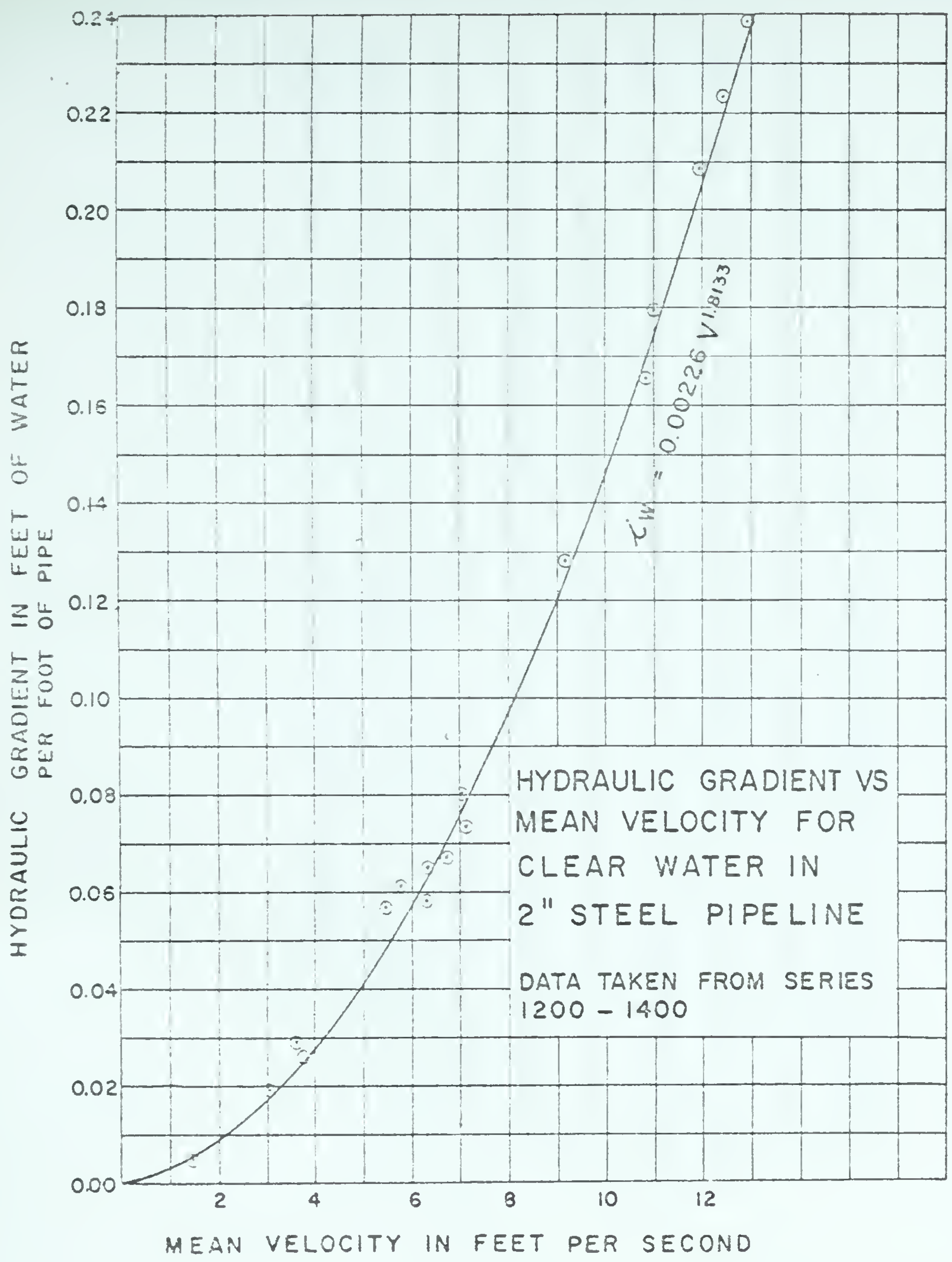


FIGURE IV - 1

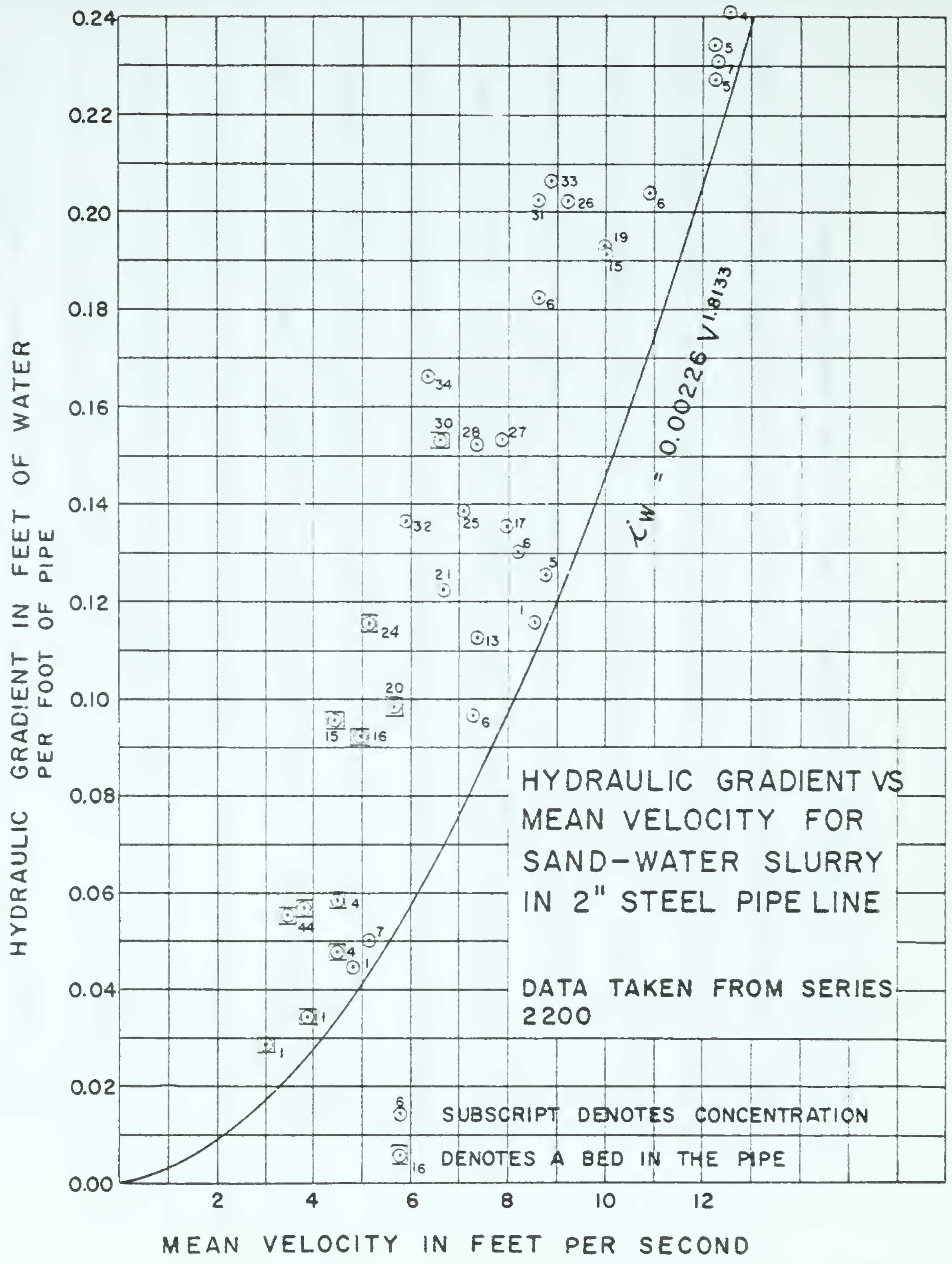


FIGURE IV - 2

The independent sets of data published by Hazen, Hardy and Blatch established that the hydraulic gradient for sand-water slurries was greater than that for clear water in the pipelines tested. They all concluded that there was some minimum velocity, which has been defined herein as the "critical deposit velocity", at which a bed forms in the pipeline. Miss Blatch confirmed these laboratory-scale observations with three sets of data obtained from dredge discharge lines, which were 30 inches or greater in diameter. Her data in a 1" brass pipe using 60-100 mesh sand showed this minimum at a velocity of approximately 3.5 ft./sec. She could explain this with the presence of a fixed bed in the pipe, which decreased the bore of the pipe with an attendant increase in head loss. Unfortunately, her data at higher concentrations are somewhat scanty and show this minimum more from intuition than actual plotted data.

After plotting their data, Hardy and Hazen as well as Blatch concluded that these lines could be expressed as the hydraulic gradient due to water alone at a given velocity plus an incremental value which was a function of the concentration of sand. Miss Blatch noted that the incremental hydraulic gradient was very high in the case of a 1-inch pipe and relatively low in the case of a 32-inch pipe, and reported a ratio of 0.0096 : 0.0012. It is apparent that all three authors felt that the plots for different concentrations of sand would lie above and parallel to the line for clear water in the pipeline.

The next major publications on experimental data were those of Howard, O'Brien and Folsom. Howard (1939) presented data for a sand of median diameter of 0.40 millimeters in a 4" pipeline. These data were again presented on a hydraulic gradient vs. mean velocity diagram and were of the same type as those of the previous workers. Dent (1939) concurred with previous work as to the shape of the curves and concluded that the curves do not converge but lie parallel to the clear water line. O'Brien and Folsom (1939) found just the opposite, in that they concluded that, above the critical velocity, the hydraulic gradient rapidly approaches and becomes identical to that for clear water.

The most exhaustive study carried out for sand in pipelines was done by Durand et al (1952). This work included a range of particle sizes up to approximately one inch in diameter for concentrations of up to approximately 50% by weight, with pipe sizes from 1" to 28". The traditional plot of hydraulic gradient vs. mean velocity was presented by Durand for purposes of data identification. However, for data analysis, he resorted to a non-dimensional plot which is discussed in Section 4.6.

Since 1952 there have been numerous publications of data collected in small pipelines. There have also been descriptions and some measurements reported on large prototype installations in both the technical and trade journals.

4.3 Flow Regimes for Fluidized Solids in a Pipeline:

Durand (1952) proposed a classification for suspension identification based upon particle sizes of the suspended solids. He classified homogeneous fluids as those which included material with particle sizes of up to about 25 microns. The intermediate identification was for particles in the size range of 25 to 50 microns and the classification of the heterogeneous suspension for material was over 50 microns. The heterogeneous suspension implied a pronounced concentration gradient across the pipe vertical diameter. Govier and Charles (1961) concurred with the classification and the author feels that it is quite adequate.

The first description of the mechanics of transport of the sand in a pipeline were given by Blatch (1906). Basically, she described the mixture at high velocities above the critical deposit velocity as moving as a suspension without a bed formation on the bottom of the pipe. As the velocity was decreased and approached the critical deposit velocity, saltating sand grains were observed on the bottom of the pipe. Once the critical deposit velocity had been reached, a solid bed formed over the bottom of the pipe. This general description has been accepted since that time with very minor modification.

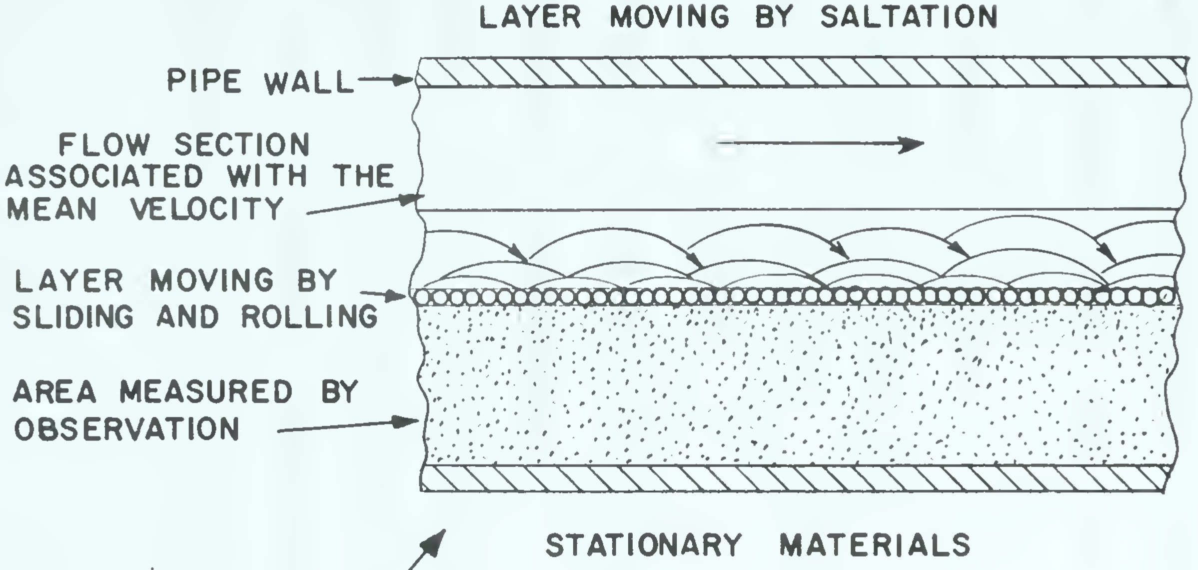
These general descriptions seem somewhat vague, but have apparently remained unchallenged until very recently. Condolios and Chapus (1963) have discussed the configuration of a deposited sand bed in pipelines. They state that the bulk of the bed is stationary with an approximate flat surface and that saltating particles

move over this bed. FIG. IV-3, which is taken from their paper, illustrates this. The author has observed different types of bed conditions within the transparent section of the test apparatus. PLATE IV-1 shows the presence of a dune formation in the pipeline. The author is of the opinion that there are at least two, if not three, different bed configurations within the pipeline, depending on the flow conditions. This behaviour is therefore quite analogous to that described by Gilbert (1914) for flumes and Blench (1957) for canals and rivers.

This description of the bed configuration is quite important. The presence of dunes or antidunes will give a much rougher lower boundary than that of the remaining perimeter of the pipe. Since Condolios and Chapus have calculated theoretical clear water pressure drops for pipes with a bed formation present, the relative roughness of the boundaries should be considered.

4.4 Distribution of Solids in the Pipeline for Sand-Water Slurries:

Although the critical deposit velocity concept and the fully-suspended flow regime have been widely accepted, there has been considerable controversy on the subject of distribution of the solids during fully-suspended flow. This discussion has centered around those materials classified as a "heterogeneous suspension" by Durand, whereas the concept of a homogeneous fluid having a uniform dispersion is fairly readily accepted.

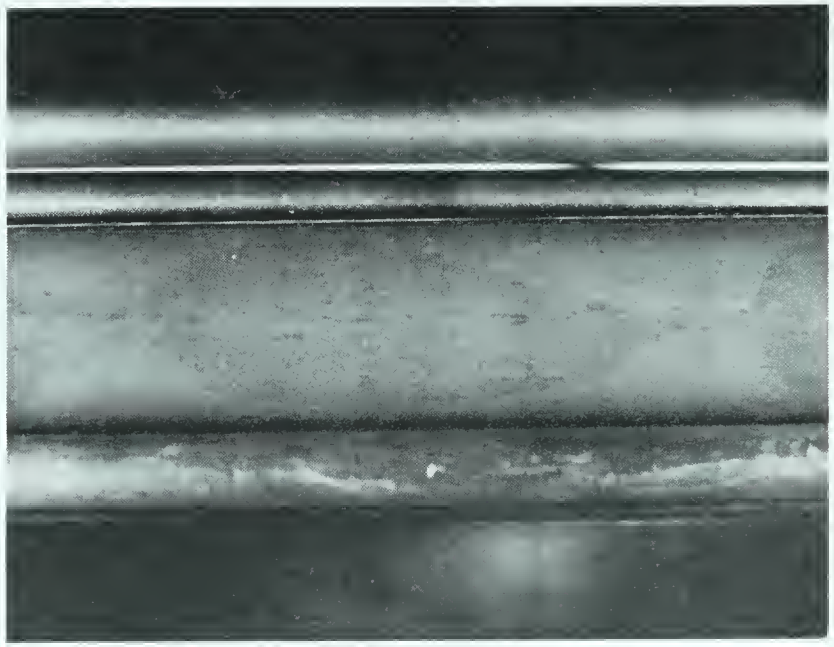


FLOW AND DEPOSIT PATTERNS IN A HORIZONTAL PIPELINE

FIGURE IV - 3
(AFTER CONDOLIOS & CHAPUS 1963)

← FLOW DIRECTION

TRANSPARENT PIPE
PLAN VIEW



← FLOW DIRECTION

TRANSPARENT PIPE
SIDE VIEW

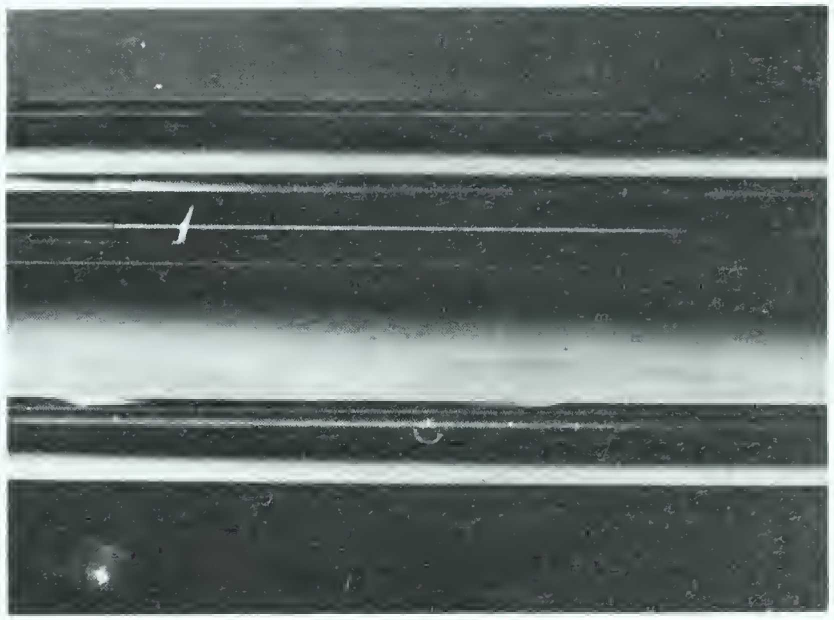
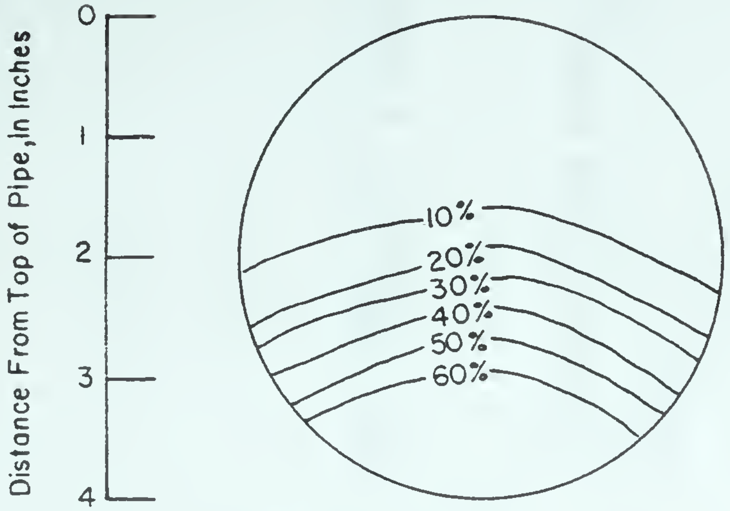


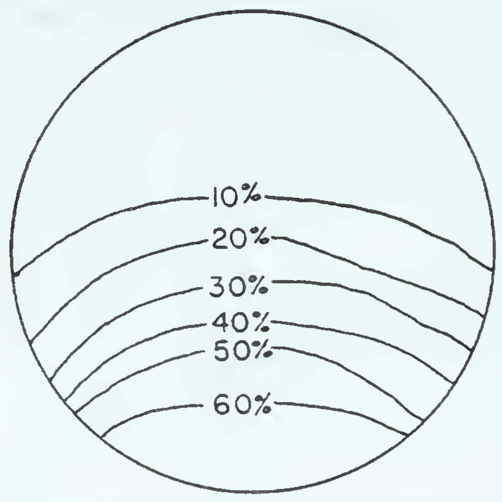
PLATE IV - I

The first data on concentration distribution and pipeline for heterogeneous flow was put forth by Howard (1939). FIG. IV-4 is a curve taken from his 1939 paper, showing concentration distributions for completely-suspended flow of a heterogeneous fluid in different size pipelines. Danel (1939) thought that this type of distribution was more likely to be encountered in open-channel flow and contended that the distribution in pipelines would approach that of Curve "A" or "B" on FIG. IV-5, which is taken from his 1939 discussion on Howard's paper. Much evidence was subsequently gathered by other workers, which confirms the distribution pattern advocated by Howard. After considerable experimenting, Durand (1952) concluded that the concentration distribution was even greater near the bottom of the pipe than that proposed by Howard.

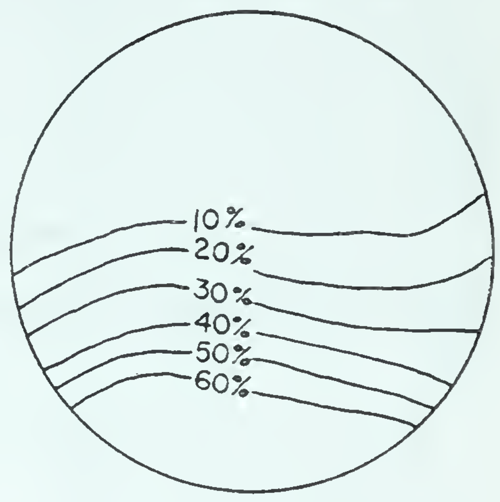
Although the author has made no direct concentration measurements on the laboratory test apparatus, he has had opportunity to inspect many large prototype pipelines handling sand-water slurries. In all cases, an examination of the wear pattern on the inside of the pipe indicated severe abrasion at the invert of the pipe, decreasing fairly uniformly to approximately 4 o'clock and 8 o'clock on the pipe's sidewalls. The pipeline was virtually non-eroded above the centre. This field evidence confirms the data of Durand and it convinces the author that the greatest bulk of the sand is transported in a very dense concentration immediately above the bottom of the pipeline.



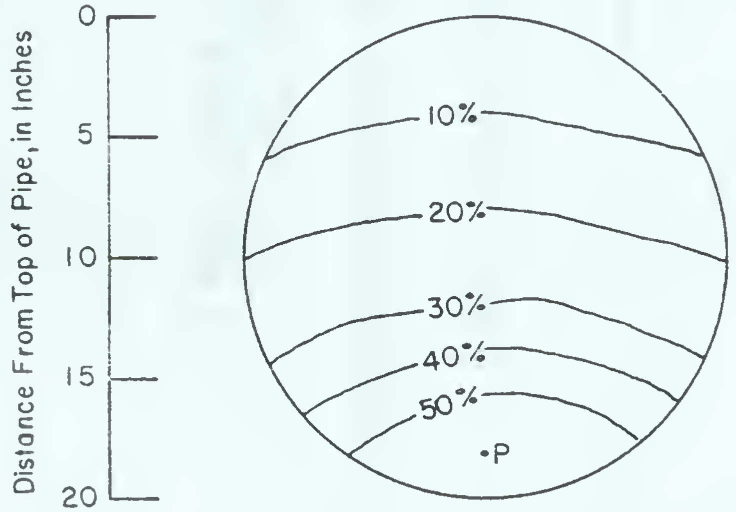
(a) Velocity, 6.0 Ft per Sec; Percentage of Solids, 13.3; Sand Settled on Bottom. Diameter of Pipe, 4 In.



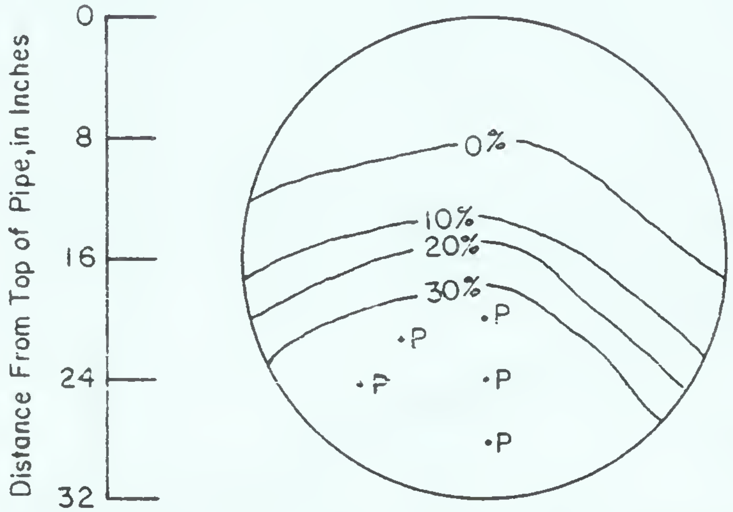
(b) Velocity, 7.3 Ft per Sec; Percentage of Solids, 15.0; Sand Settled on Bottom. Diameter of Pipe, 4 In.



(c) Velocity, 8.9 Ft per Sec; Percentage of Solids, 14.4; Sand Settled on Bottom. Diameter of Pipe, 4 In.

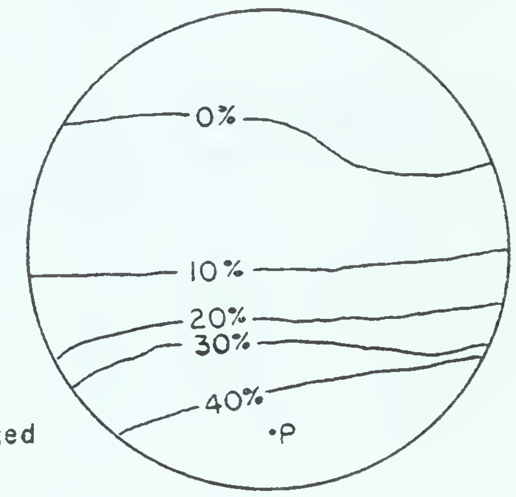


(d) Velocity, 21.0 Ft per Sec; Percentage of Solids, Unknown. Diameter of Pipe, 20 In.



(e) Velocity, 14.8 Ft per Sec; Percentage of Solids, 13.3. Diameter of Pipe, 32 In.

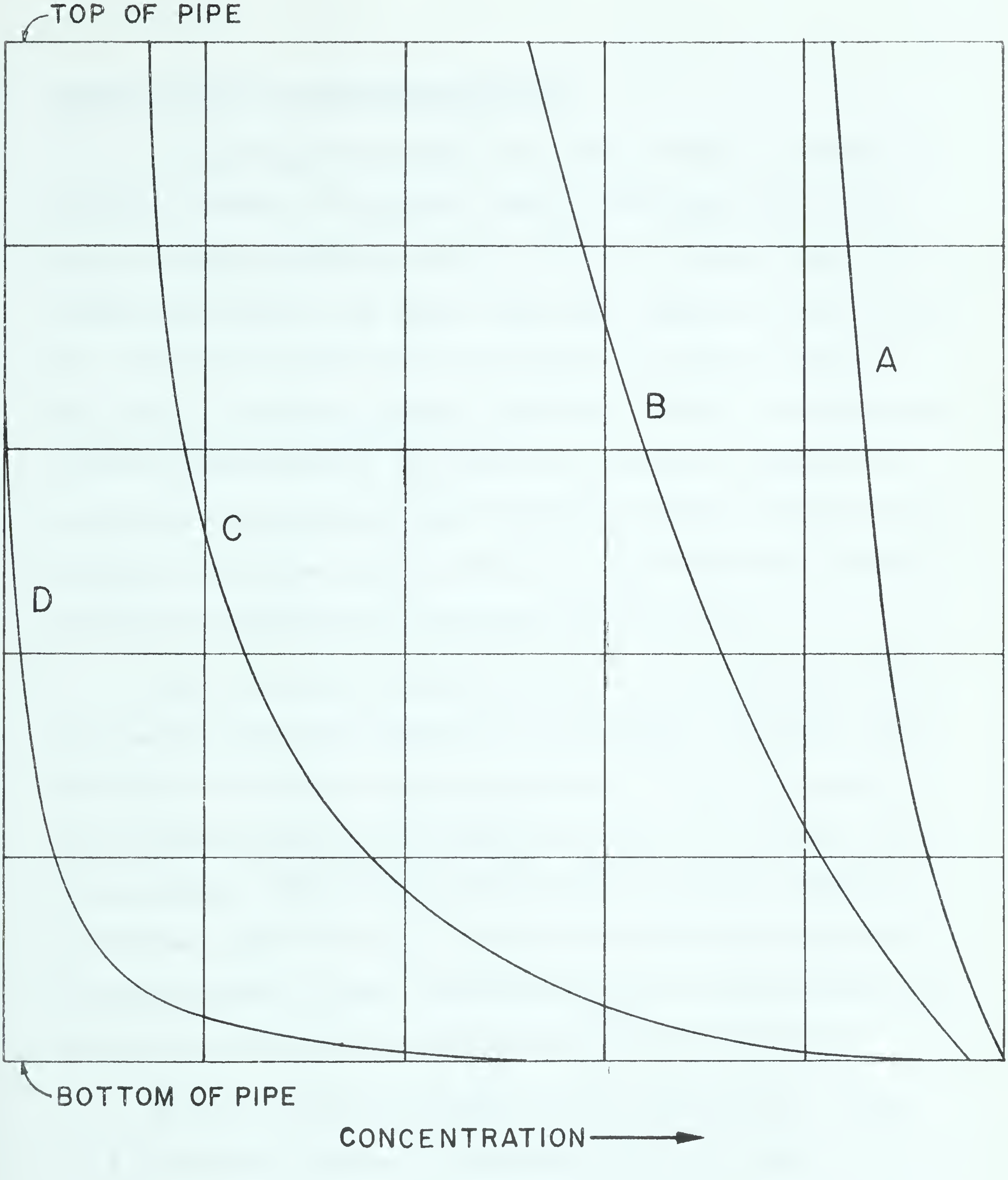
P Denotes Point at Which Sampler Plugged



(f) Velocity, 21.8 Ft per Sec; Percentage of Solids, 18.2. Diameter of Pipe, 32 In.

FIGURE IV - 4

(AFTER HOWARD 1939)



SOLIDS DISTRIBUTION FOR SAND-WATER SLURRIES IN A PIPE LINE

FIGURE IV - 5

(AFTER P.F. DANEL, 1939)

4.5 Friction Factor for Sand-Water Slurries:

As previously mentioned, the published data were plotted as hydraulic gradient vs. velocity. Howard (1939) gave tables of his data as well as plotting the results. It is a very simple matter to convert these plots to the Stanton diagram presentation of CHAPTER III. The historical data plot in much the same manner as those of FIG. III-2. The author concurs with Howard (1939) and Montgomery (1939) in concluding that, for sand-water mixtures in pipelines for velocities in the transition range immediately above critical deposit velocity, the friction factor is inversely proportional to the velocity and directly proportional to the concentration of sand.

Since the curves of friction factor vs. Reynolds number tend to converge on the clear water line as the velocity increases, there has been a tendency by many theoreticians to accept the premise that the friction factor for slurries is the same as for water in the same pipeline. Others have concluded that the results of O'Brien and Folsom (1939) are valid, in that the friction factor of any given Reynolds number is equal to the friction factor at that Reynolds number for water multiplied by the specific gravity of the mixture.

Since it is generally agreed that the best operating velocity for a commercial pipeline is immediately above the critical deposit velocity, neither of the aforementioned conclusions is particularly pertinent. The most important range of operating condition is that shown in FIG. III-2, which indicates very wide variations in the value of the friction factor with respect to small changes in the Reynolds

number. If the friction factor were to enter into a formula which could be used to predict the operating conditions in this range of Reynolds number, it is obvious that a value based on water results or such a value multiplied by the specific gravity of the slurry could not be correct.

4.6 Correlations for Hydraulic Gradient of Sand-Water Slurries:

The work of Durand (1952) initiated a series of analyses of existing data by several independent workers. The general approach employed by all was one of dimensional analysis. The basic idea was to develop a non-dimensional correlation which could be used to predict the slurry head losses for all the flow regimes described in Section 4.3.

The conclusion of O'Brien and Folsom (1939) that the settling velocity of the solid particles was the most pertinent variable greatly influenced the thinking of the theoreticians. They quickly recognized the potential of grouping the variables, specific weight of solids, shape and size of solids particles, viscosity and specific weight of the homogeneous fluid phase into one parameter of settling velocity of the solids particles. Since it was generally agreed that sand-water slurries exhibited a greater hydraulic gradient than for that of water alone, the approach was to find a parameter including actual hydraulic gradient of slurry, equivalent hydraulic gradient of water and concentration of solids.

The two most widely accepted correlations are those of Durand (1952) and Newitt et al (1955). The Durand equation is -

$$\Phi = \frac{i - i_w}{C_s\, i_w} = K_5 \left[\frac{gD\left(\frac{\gamma_p}{\gamma_w} - 1\right)}{V^2} \quad \frac{W}{\sqrt{gd\left(\frac{\gamma_p}{\gamma_w} - 1\right)}} \right]^{1.5} \quad \ldots\ldots\ldots \quad (4\text{-}2)$$

where -

i = Hydraulic gradient of slurry in feet of water per foot of pipe;

i_w = Hydraulic gradient of clear water in pipe at the same mean velocity;

C_s = Concentration of sand in per cent by volume;

K_5 = An empirical constant;

g = Acceleration due to gravity;

γ_p = Specific weight of the solids;

γ_w = Specific weight of the water;

W = Terminal settling velocity of a solid particle in water;

V = Mean velocity in the pipeline;

d = Diameter of the solid particle;

D = Diameter of pipeline.

This expression was based on extensive experimental data over a wide range of solids materials and pipe sizes. The Newitt equation is -

$$\frac{i - i_w}{C_s\, i_w} = K_6 \left(\frac{\gamma_p}{\gamma_w} - 1\right) \frac{WgD}{V^3} \quad \ldots\ldots\ldots\ldots\ldots \quad (4\text{-}3)$$

The Newitt equation was arrived at theoretically, with the constant K_6 assigned experimentally. A discussion of the equation has been given by Newitt (1955) and Howard (1962). Essentially, the approach was one of attempting to equate the work done by the falling particles to the work done on the particles.

FIG. IV-6 is a plot of -

$$\frac{i - i_w}{C_s\, i_w} \quad \text{vs.} \quad \left[\frac{gD\left(\frac{\gamma_p}{\gamma_w} - 1\right)}{V^2} \quad \frac{W}{\sqrt{gd\left(\frac{\gamma_p}{\gamma_w} - 1\right)}} \right]$$

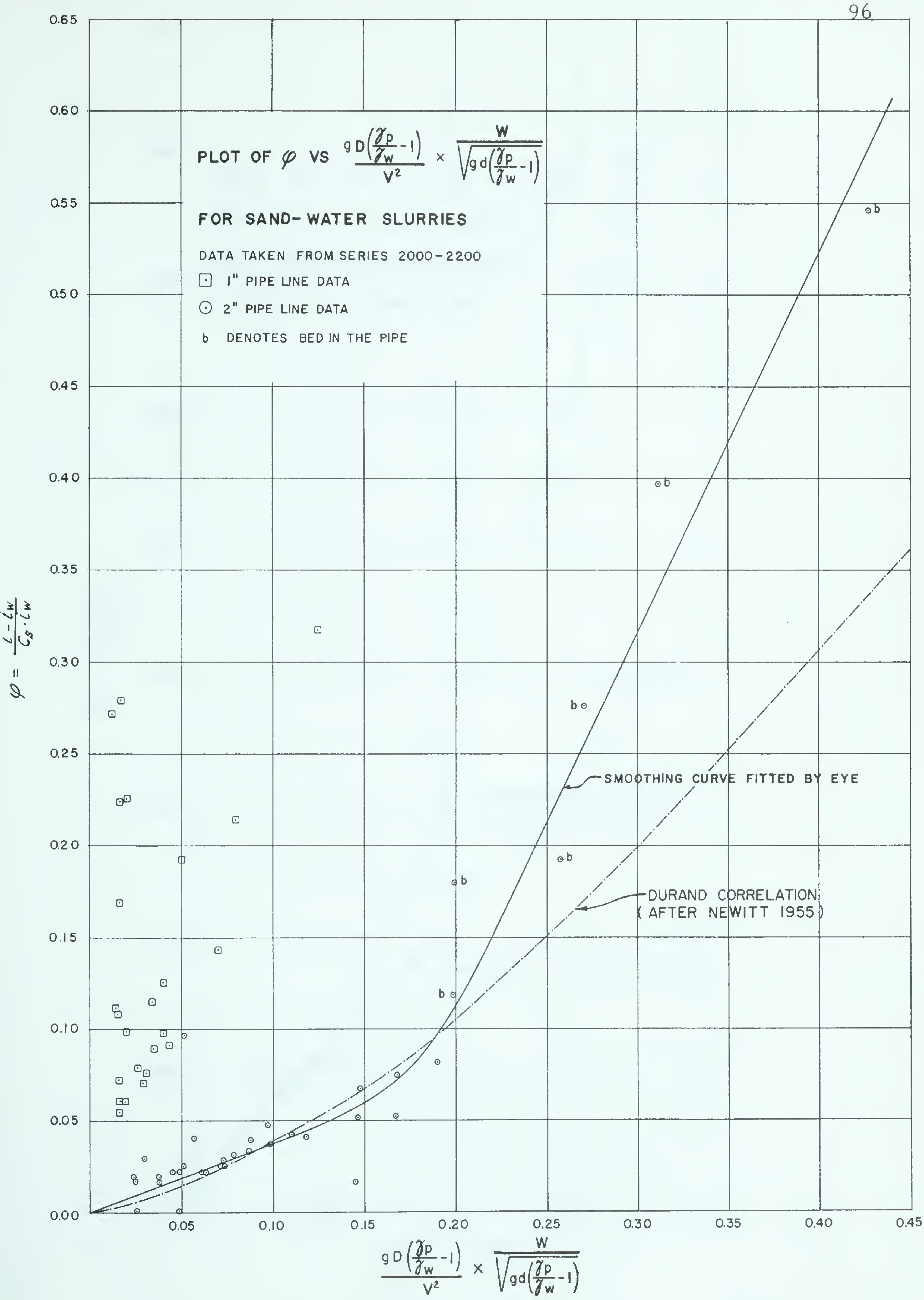
for the sand slurries of Series 2000 - 2200. The settling velocity W has been taken as 0.085 feet per second for the sand particles. This value was selected as an average of the two values given for sand of 0.25 mm. by Durand (1952) and Worster (1952). The correlation established by Durand is marked on the figure. The data for the 1" pipe differ markedly from the correlation. The 2" pipe results follow the general trend but do not coincide, as can be seen by the divergence of the best fit curve (drawn by eye) and the correlation line. The low-velocity data which lie above the Durand line are all associated with a bed formation.

FIG. IV-7 is a plot of -

$$\frac{i - i_w}{C_s\, i_w} \quad \text{vs.} \left(\frac{\gamma_p}{\gamma_w} - 1\right) \frac{W g D}{V^3} \quad \text{for the sand slurries of Series 2200.}$$

Again, the settling velocity has been taken as 0.085 feet per second. The data for the 1" pipe (Series 2000) are not shown, since they again lie well above the 2" pipe data. The Newitt correlation fits the data quite well for high velocities, but diverges sharply at lower velocities. The data associated with a bed condition lie well above the Newitt line.

Both the Durand and the Newitt correlations state that Φ is inversely proportional to the third power of velocity. The author's data coincide best with the Newitt correlation at high velocities but



PLOT OF φ VS $\frac{gD\left(\frac{\gamma_p}{\gamma_w}-1\right)}{V^2} \times \frac{W}{\sqrt{gd\left(\frac{\gamma_p}{\gamma_w}-1\right)}}$
FOR SAND-WATER SLURRIES
DATA TAKEN FROM SERIES 2000-2200
1" PIPE LINE DATA
2" PIPE LINE DATA
b DENOTES BED IN THE PIPE
SMOOTHING CURVE FITTED BY EYE
DURAND CORRELATION (AFTER NEWITT 1955)
$\varphi = \frac{i - i_w}{C_s \cdot i_w}$
$\frac{gD\left(\frac{\gamma_p}{\gamma_w}-1\right)}{V^2} \times \frac{W}{\sqrt{gd\left(\frac{\gamma_p}{\gamma_w}-1\right)}}$

FIGURE IV - 6

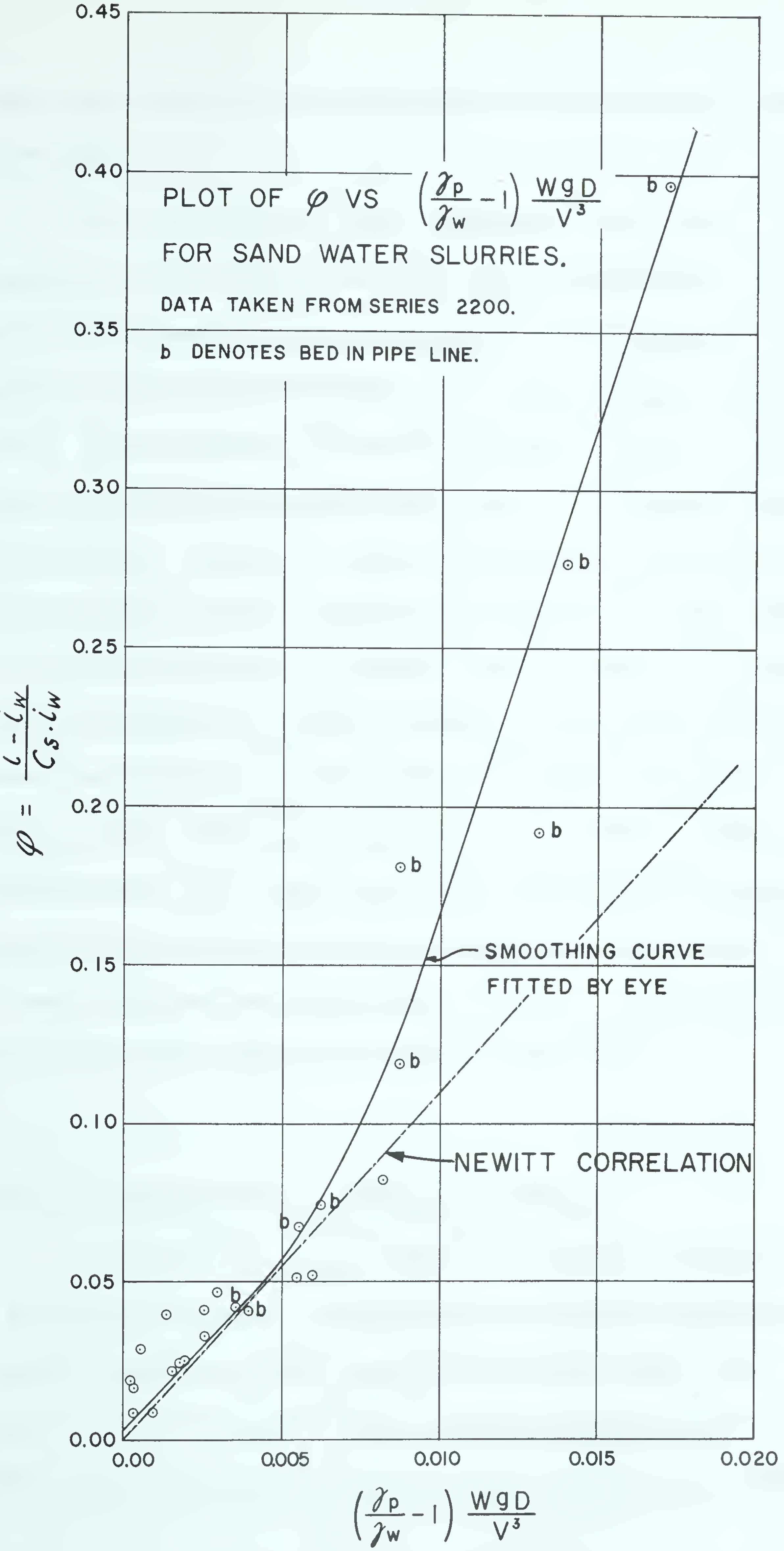

PLOT OF φ VS $\left(\frac{\gamma_p}{\gamma_w}-1\right)\frac{WgD}{V^3}$
FOR SAND WATER SLURRIES.
DATA TAKEN FROM SERIES 2200.
b DENOTES BED IN PIPE LINE.
SMOOTHING CURVE FITTED BY EYE
NEWITT CORRELATION
$\varphi = \frac{i - i_w}{C_s \cdot i_w}$
$\left(\frac{\gamma_p}{\gamma_w}-1\right)\frac{WgD}{V^3}$
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.00
0.005
0.010
0.015
0.020
b

FIGURE IV - 7

differ significantly from both at low velocities with bed formations in the pipe.

The correlations shown in Equations (4-2) and (4-3) are both dependent on the settling velocity of the solid particles. The settling velocity has been calculated for settling rate in the intermediate range just above that of Stokes Law for spherical particles in clear water. Unfortunately, this settling velocity is not very meaningful, since the settling is actually taking place in a fluid which has a density gradient. Consider a slurry of sand-in-water with a solids concentration of 20% by volume in a 6" pipeline. If the concentration gradient measured by Durand (1952) is accepted, approximately 85% of the solids are within 1.2 inches of the invert of the pipe. This means that in this lower zone the concentration of solids is actually 60% by volume, which corresponds to a fluid with specific gravity of approximately 2.0. This calculation illustrates the presence of a high-gravity fluid near the bottom of the pipe which would offer significantly different settling characteristics for individual sand grains than would clear water or a relatively thin slurry.

4.7 Effect of Particle Size in Sand-Water Slurries:

Condolios and Chapus (1963) investigated pipeline transport of different-size sands and found that the hydraulic gradient for the coarser sands was greater than that for finer sands. FIG. IV-8 is a plot of Φ vs. V for their test results, together with those of the 2000 - 2200 Series of this investigation. They continued this type of

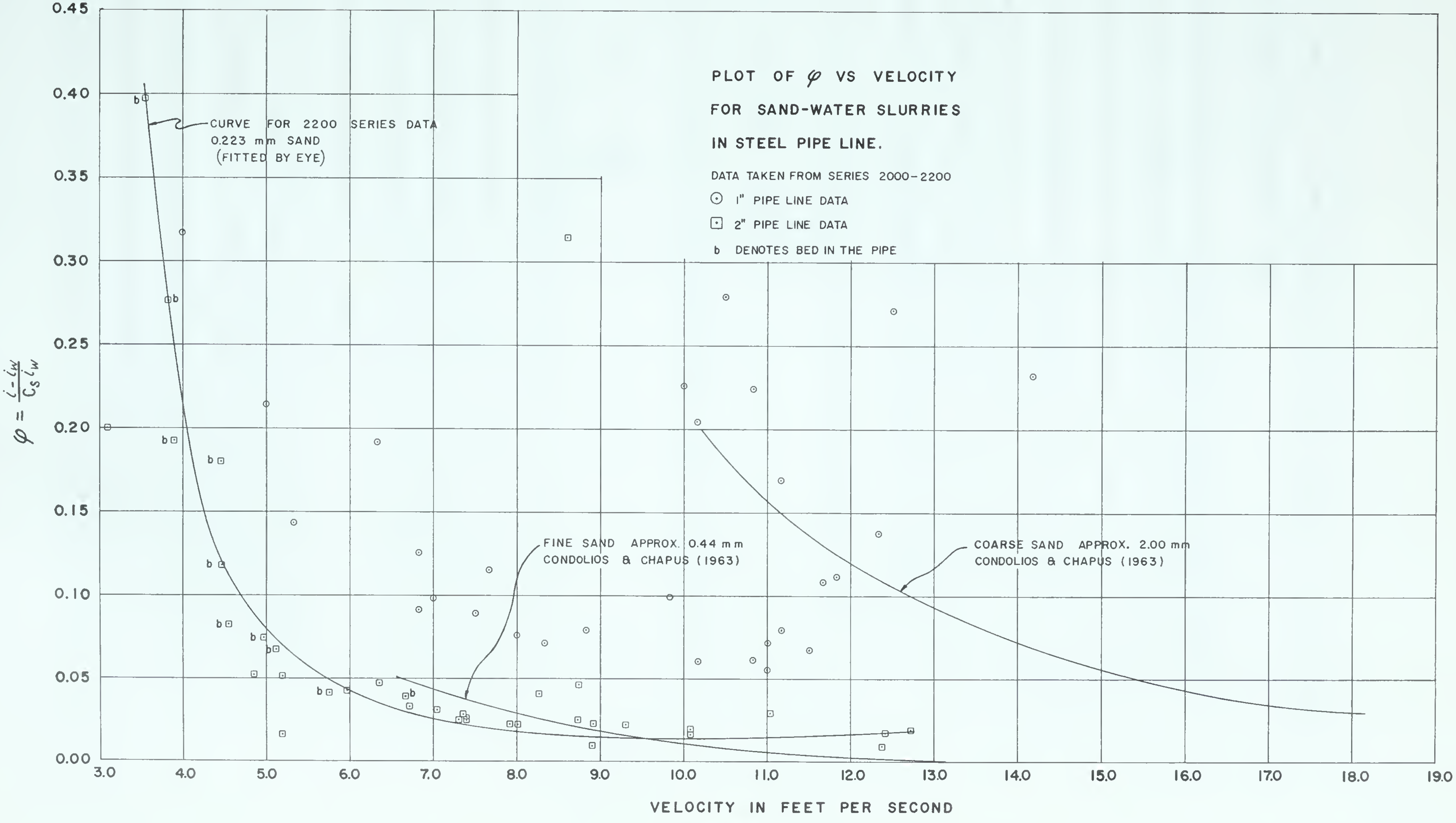

PLOT OF φ VS VELOCITY
FOR SAND-WATER SLURRIES
IN STEEL PIPE LINE.
DATA TAKEN FROM SERIES 2000-2200
1" PIPE LINE DATA
2" PIPE LINE DATA
b DENOTES BED IN THE PIPE
CURVE FOR 2200 SERIES DATA
0.223 mm SAND
(FITTED BY EYE)
FINE SAND APPROX. 0.44 mm
CONDOLIOS & CHAPUS (1963)
COARSE SAND APPROX. 2.00 mm
CONDOLIOS & CHAPUS (1963)
φ = (i - iw)/(Cs iw)
VELOCITY IN FEET PER SECOND
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
17.0
18.0
19.0

FIGURE IV - 8

study and found that for particles greater than 2 mm. the head losses were independent of particle size.

This phenomenon was explained by Condolios and Chapus in terms of the drag coefficient for particles of greater than 2 mm. Experimental work has shown that the drag coefficient for spherical particles is fairly independent of Reynolds number (in terms of particle diameter) for values in the range 1000 to 200,000. To accommodate the irregularity of particle shape, a sphericity factor was introduced and the drag coefficient was modified to include it.

The correlation known as the Durand-Condolios Law is -

$$\Phi = K_7 \left[\frac{V^2}{gD} \sqrt{C_{x^1}} \right]^{-\frac{3}{2}} \quad \ldots \ldots \quad (4\text{-}4)$$

where C_{x^1} is the apparent drag coefficient, which is defined by the relation -

$$C_{x^1} = \frac{C_x}{\Psi} \quad \ldots \ldots \quad (4\text{-}5)$$

where C_x is the drag coefficient of a sphere of equal volume to a given angular particle and Ψ is a sphericity factor defined by the ratio of the maximum cross-sectional area of a sphere of diameter equal to the median diameter of the solid particles and the area of the largest cross-section of the particles.

During the experimental work at the University of Alberta, a few crude settling tests were carried out on the sand grains in a graduated cylinder, yielding a settling velocity of 0.127 feet per second. The Reynolds number for this settling velocity is 7.67 (as defined by $\frac{Wd}{\nu}$), which corresponds to a drag coefficient of C_x = 5.0

in terms of the results shown by Condolios and Chapus. The Alberta test sand has been described as well-rounded and could be assigned a sphericity of $\psi = 1.0$. In this case, $C_{x'} = C_x$ and Equation (4-4) reduces to Equation (4-2) in the manner described by Babcock (1962). A plot for the Alberta test sand in the 2" pipeline can be seen in FIG. IV-6.

4.8 Critical Deposit Velocity for Sand-Water Slurries:

Although most of the investigations described in the literature have attempted to establish the critical deposit velocity at which a bed forms on the bottom of the pipe, testing has been carried out for a given material for a limited range of concentrations. The only empirical correlation published to date is that of Durand (1952), in which he related the Froude number to the concentration in the form -

$$\frac{V_c}{\sqrt{2gD\left(\frac{\gamma_p}{\gamma_w} - 1\right)}} = \text{fn}\ (C_s) \quad \ldots\ldots\ldots\ldots \quad (4\text{-}6)$$

Howard (1962) has shown that this correlation does not agree with the Alberta results. He found that a better correlation was obtained for -

$$\frac{V_c \left(\frac{\gamma_p}{\gamma_w} - 1\right)}{\sqrt{2gD}} = \text{fn}\ (C_s) \quad \ldots\ldots\ldots\ldots \quad (4\text{-}7)$$

when using the data from the 2000 - 2200 Series of tests.

The author has carried out a critical deposit velocity investigation for the 2200 Series of tests. This is discussed in detail in Section 6.5.

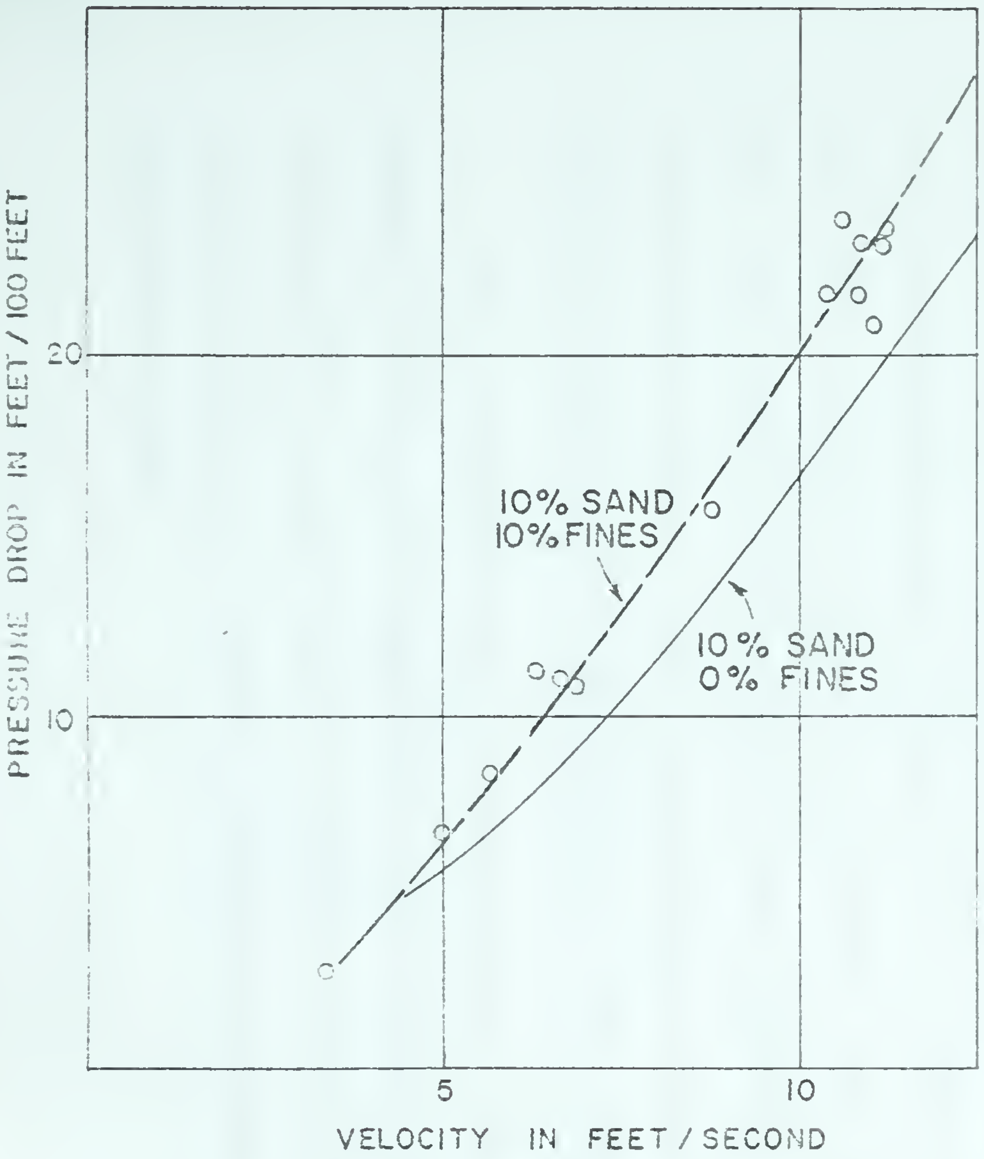
4.9 Effect of Fines on Sand-Water Mixtures:

Previous mention has been made of the beneficial effect of fines on a sand-water slurry. The practical experience has been that the inclusion of fines has increased the sand-carrying capacity of a pipeline at a constant discharge rate.

Newitt (1955) noted this boosting effect and suggested that the homogeneous fines-water slurry reduced the sand sedimentation rate. He believed that this would result in a more uniform sand dispersion, thus reducing the very dense slurry at the invert of the pipe.

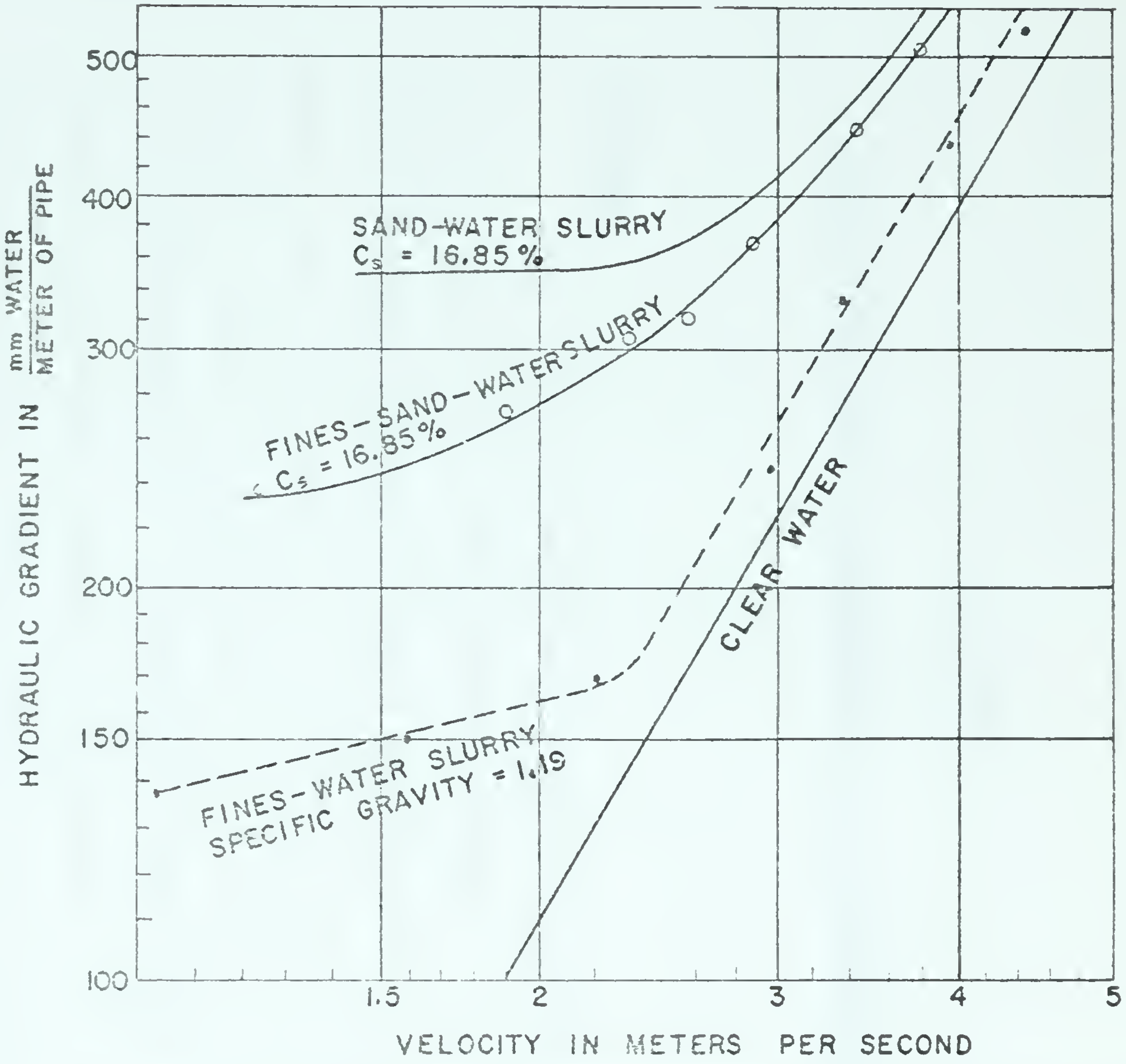
Howard (1962) analysed the fines-sand-water slurry data of Series 5400 included herein. He concluded that the critical deposit velocity for a given sand concentration could be reduced by the inclusion of fines. FIG. IV-9 shows the convergence of the hydraulic gradient curves for 10% sand slurry, with and without fines. At higher velocities the curves diverged, thus indicating that the fines increased the hydraulic gradient at high velocities.

Condolios and Chapus (1963) stated that the addition of fines reduces the hydraulic gradient of a sand-water slurry at a given discharge rate. FIG. IV-10, taken from their paper, shows this effect.



EFFECT OF 10% FINES ON A 10% SAND SLURRY

FIGURE IV -9
(AFTER HOWARD-1962)



HEAD LOSS CURVE FOR A GRANULAR SAND TRANSPORTED IN A SUPPORTING, HOMOGENEOUS MIXTURE

FIGURE IV - 10
(AFTER CONDOLIOS AND CHAPUS - 1963)

CHAPTER V

OPEN-CHANNEL TRANSPORT OF FLUIDIZED SOLIDS

5.1 General:

This chapter describes the physical phenomena observed during the experimental work on flume transport of fluidized solids. The most distinctive feature of flume experiments was the antidune formation in the flume, which is described herein in considerable detail. The very limited carrying capacity of the flume for sand-water slurries is discussed and a correlation for the critical deposit velocity of these sand-water slurries is developed. The beneficial effect of the inclusion of fines into the slurry is also discussed.

There are some rather descriptive papers outlining the operations of various tailings disposal applications of flume transport. Any data available on these commercial operations are of limited value, since they are taken on one constant set of operating conditions. The author believes that the only published experimental information to date are those reported for the University of Alberta research program (Ansley and Hebbert, 1961); (Ansley, 1962).

The two parameters of critical deposit velocity and energy gradient are far more important in open-channel flow than for pipeline transport. In the case of a pipeline, pumps can be added if absolutely necessary, whereas geographical location quite often limits flume slope.

5.2 Flow Regimes in the Flume:

All the flume studies reported herein were carried out in the super-critical or rapid-flow regime. In all cases, the Froude number in terms of velocity squared exceeded unity. The desirable operating condition for the flume was one of a clean bed, which is defined as that flow regime in which no individual solid particle was in continuous contact with the wooden bottom of the flume.

The first appearance of a discrete bed formation was considered the point of transition from the normal operating condition to an undesirable regime and was defined as the "critical deposit condition." This critical deposit condition was determined experimentally by either decreasing the discharge or increasing the sand concentration. Just before critical conditions were reached, significant quantities of saltating sand grains were in contact with the flume bed. The critical deposit condition was characterized by a local deposit, which is defined as an "antidune." If the critical deposit condition were passed, a so-called "partial bed" was observed, which consisted of a fairly continuous build-up of solids in the corners of the flume, with saltating particles running in the centre. The next condition is defined as a "jerking bed," in which the centre of the flume had a thin film of sand moving intermittently down the flume. The final condition is that of a "continuous bed," which remained stationary with respect to the flume.

The formation of antidunes was found to be fairly systematic and a considerable amount of laboratory time was taken up in studying their behaviour. Since the formation could be studied in the flume and indicated critical deposit conditions, a fairly lengthy description is included herein.

5.3 Antidunes for Sand-Water Slurries:

The formation of an antidune was dependent on both the discharge rate and the concentration of sand. When these factors were adjusted to approach the critical condition, the antidune deposit could be initiated by some disturbance in the flow. In most cases, the disturbance resulted from a change in flow pattern caused by the flume configuration. However, it was often possible to induce an antidune in an apparently stable flow regime by partially obstructing the flow for a few seconds. If the flow regime were at the critical condition, it was often possible to prevent the formation by constant removal of deposited solids at the downstream exit of the flume. It was concluded that antidunes do not form initially in the straight, constant-slope, uniform cross-sectional reaches of the flume.

A change in flow pattern caused a small amount of sand to deposit against one wall of the flume, immediately downstream of the disturbance. This deposit quickly formed into a bar about 2 inches long, 1" wide and $\frac{1}{2}$" deep, which deflected the flow pattern against the opposite wall of the flume. A new bar then started to form immediately downstream of the point of impact of the flow. The flow was then deflected back against the first wall and in this manner developed a sinusoidal flow path down the flume between regularly-spaced sand bars, as shown in FIG. V-1. These small deposits grew in size until adjacent ones were large enough to bridge the channel width and obstruct the flow sufficiently to cause a hydraulic jump. Once a hydraulic jump had formed, the deposit causing it grew rapidly into an antidune. At this time all the smaller deposits

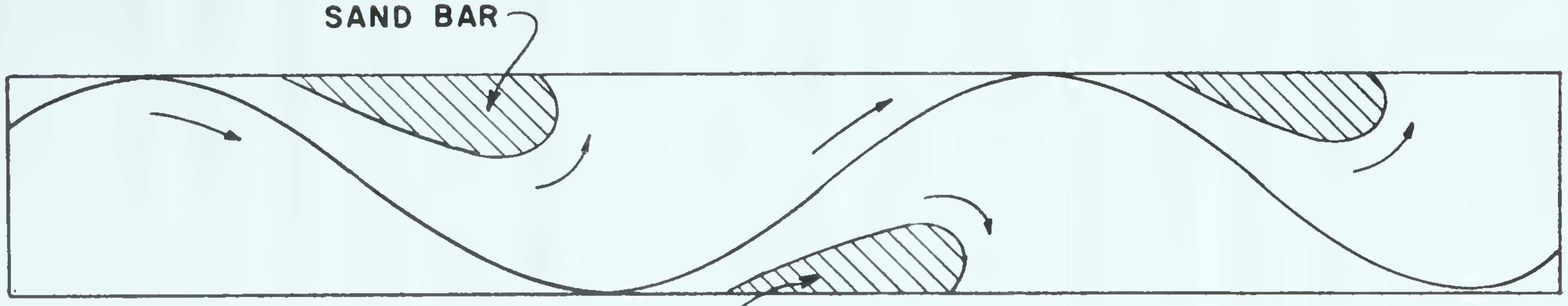
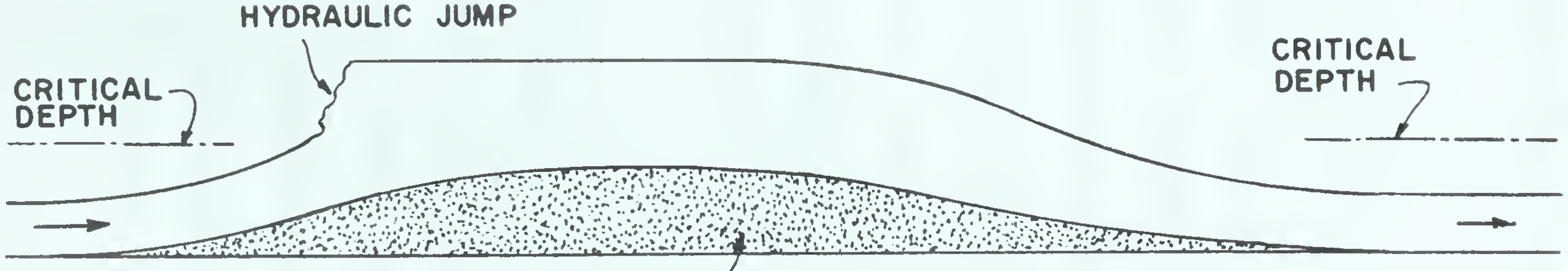


FIGURE V-1



SIDE VIEW OF THE ANTIDUNE

FIGURE V-2

TOP VIEW OF WATER SURFACE ABOVE ANTIDUNE WITH "ROOSTER TAIL"

PLATE V-1

which had not bridged the channel were eroded away, leaving the channel with a series of three or four randomly-spaced hydraulic jumps and associated antidunes. In the next interval, of 5 to 10 minutes, the antidune farthest upstream grew in length and depth at the expense of the others, which were slowly eroded away until the final steady state was reached when there was only one large antidune in the flume.

In some cases, a train of three or four antidunes appeared to remain stable, with no individual antidune growing at the expense of the others. In these cases, the whole group moved upstream simultaneously.

When antidune formation was imminent at the flume weigh tank diversion, saltating sand was observed in the transparent section of the flume some 70 feet upstream. Once an antidune formed at the diversion, the transparent section had no saltating particles.

Antidunes were also formed by ponding-up the flow in a straight, free-flowing reach of the flume. If the ponding allowed a sufficient amount of sand to settle on the flume bottom, a stable sand bed was formed which then caused the hydraulic jump and associated antidune.

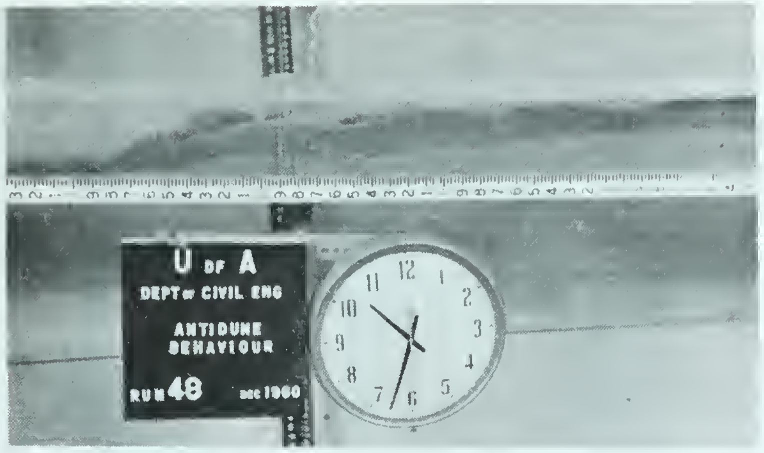
Generally speaking, the behaviour of antidunes was characterized by an upstream migration of the wave form itself, while the individual sand grains continued to move downstream. The configuration of the antidune can be seen in FIG. V-2. A photograph of the water surface can be seen on PLATE V-1. The oncoming flow deposited its load of sand at the head of the antidune as it passed through the

hydraulic jump from super-critical to sub-critical flow. At the downstream end of the antidune the sand deposit tailed off. This resulted in an increase in the effective bottom slope. The velocity of the flow therefore began to increase and passed smoothly into super-critical flow. As the flow velocity increased, the sand was picked up or scoured away, so that the overall length of the dune did not change once it had become fully established. The effect, however, of depositing sand at the head and scouring it away at the tail meant that the antidune moved upstream. It continued to move upstream until it reached the headbox, where it dissipated. As soon as it disappeared, the concentration of the slurry again became critical and another deposition cycle began, so that the whole phenomenon outlined above repeated itself.

Antidunes have been observed which increased in size, and others which decreased in size, as they moved upstream. The antidunes were generally large at high concentrations of sand in the system and were noticeably larger at steep-slope settings of the flume.

The transparent section of the flume was used for observation and measurements of the antidune configuration and velocity. Both still and motion pictures were used extensively to aid in these studies. A twelve-minute film is on file in the Department of Civil Engineering, showing several sequences of antidune movements in the flume. This film was shown at the May 1961 joint meeting of the Engineering Institute of Canada and the Hydraulics Division of the American Society of Mechanical Engineers. A sequence of still photographs can be seen in PLATES V-2 and V-3 and two additional sequences can be seen in APPENDIX "E".

1



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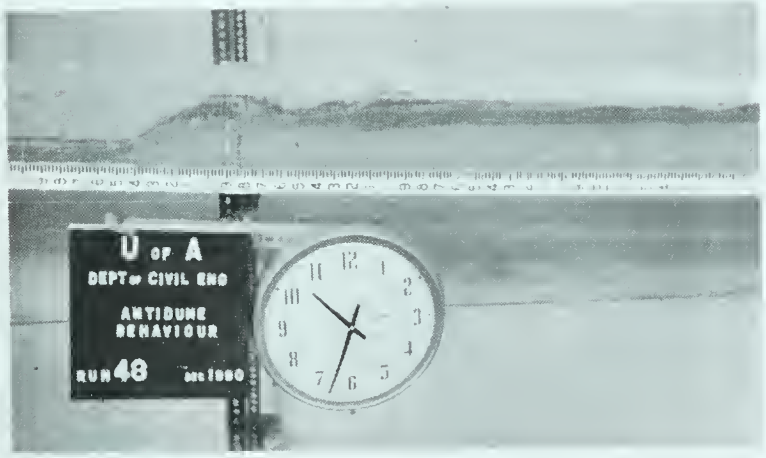

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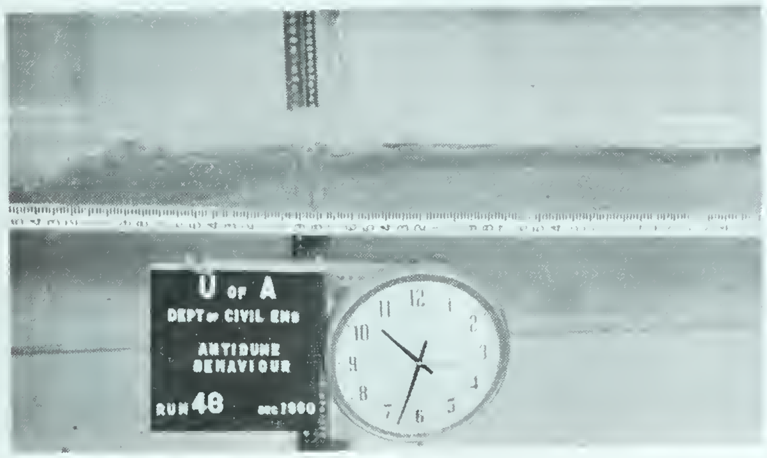

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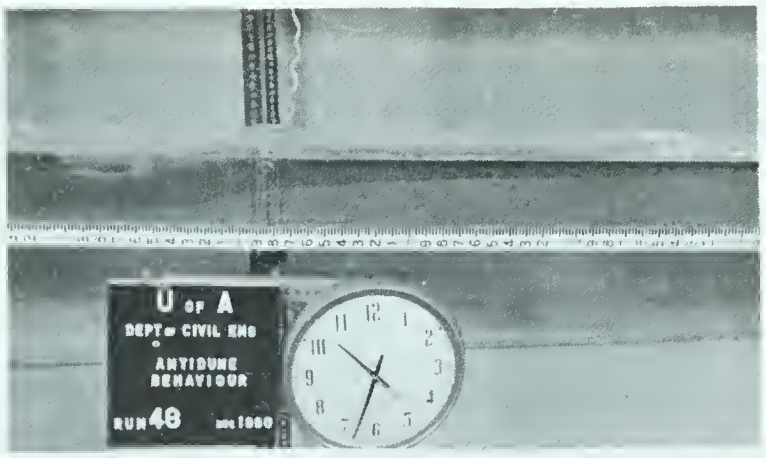

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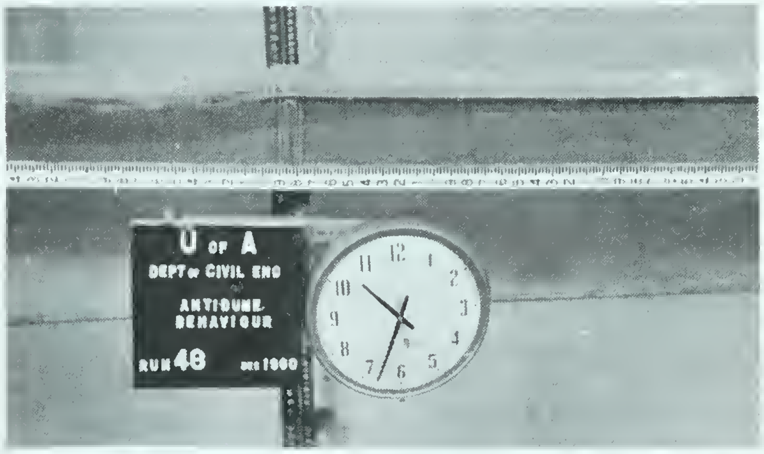

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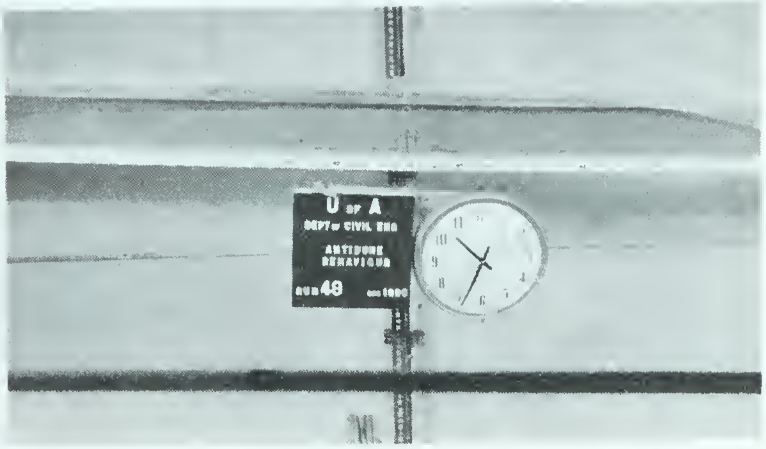
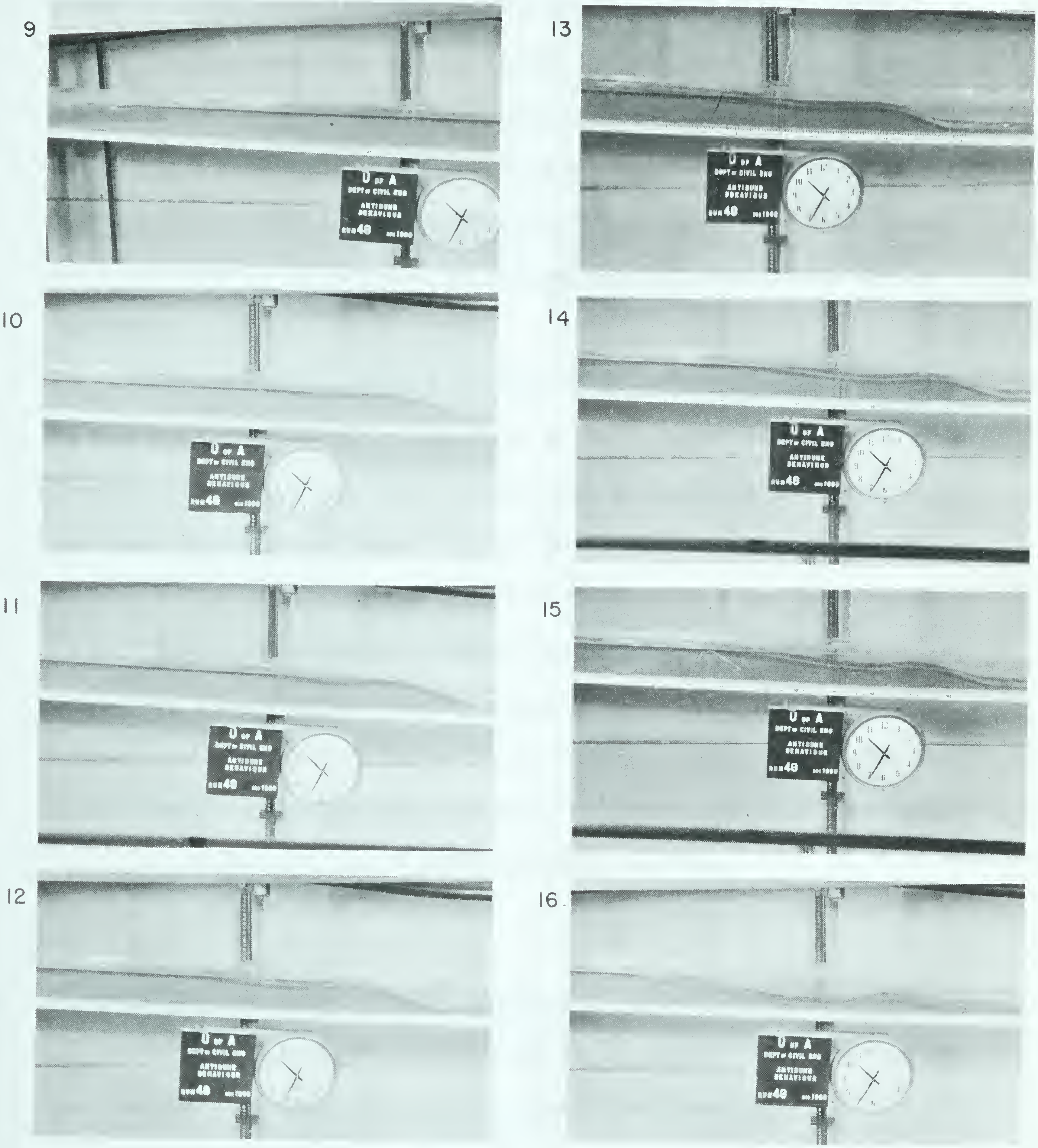


SEQUENCE OF 16 PHOTO'S SHOWING ANTIDUNE BEHAVIOUR --
DISCHARGE: 0.132 ft^3/sec. FLUME SLOPE: 4% SAND CONCENTRATION: 7% BY VOLUME

PLATE V-2



SEQUENCE OF 16 PHOTO'S — CONTINUED FROM PLATE V-2

PLATE V-3

5.4 Critical Deposit Velocity for Sand-Water Slurries in the Flume:

As discussed earlier, it is quite important that the flume be operated with a clean bed. It should be noted that, although abrasion is less of a problem in the flume than for pipelines, the wear rate of the sides and bottom is accelerated by high velocities. It is therefore desirable to determine the critical deposit velocity for design purposes.

One of the interesting aspects of the critical deposit velocity is that it represents the upper limit of the antidune bed formation. For rivers, canals and large flumes with a bed load, the lower limit has been identified in terms of the Froude number (Blench, 1957). Although this Froude number relation applied for a bed load regime at high Reynolds numbers, several times those of the author's data, it seemed a reasonable starting point for analysis. However, the author could not find a similar Froude number identification for the upper limit. A dimensional analysis of the variables was carried out to see if the data could yield a good correlation.

5.5 Dimensional Analysis for Critical Deposit Conditions:

The interrelated variables which can be considered pertinent for the sand-water slurry experiments in the flume are:

V = Mean velocity of flow in ft./sec.
b = Breadth of flow in ft.
y = Depth of flow in ft.
ϵ = Absolute roughness of boundary in ft.
g = Acceleration due to gravity in ft./sec^2.

gS = Component of gravity acceleration parallel to the flume in ft./sec.^{2}

ρ_1 = Mass density of continuous fluid phase in slugs/ft.^{3}

μ = Absolute viscosity of the fluid in $\frac{\text{lbs. sec.}}{\text{ft}^2}$

ρ_s = Mass density of the sand particles in slugs/ft.^{3}

d = Median diameter of the sand particles in ft.

C_s = Concentration of sand by volume in %.

These variables are functionally related such that -

$$fn\ (V, b, y, \epsilon, g, gS, \rho_s, d, C_s) = O \quad \ldots \quad (5\text{-}1)$$

The dimensional analysis is somewhat simplified if the kinematic viscosity is used -

$$\nu = \frac{\mu}{\rho_1} \quad \ldots \quad (5\text{-}2),$$

where the dimensions of ν are ft^2/sec.

The concentration of sand is the most important single variable from a prototype design standpoint. By forming non-dimensional groups, we find that concentration is functionally related to the remaining groups, such that -

$$C_s = fn\left(\frac{V^2}{gSy}, \frac{V^2}{gy}, \frac{b}{y}, \frac{\epsilon}{b}, \frac{\rho_s}{\rho_1}, \frac{Vy}{\nu}, \frac{\sqrt[3]{g\nu}\ d}{\nu}\right) \quad \ldots \quad (5\text{-}3)$$

As discussed in Section 2.4, the sand used in the tests can be considered constant from both a size and mass density standpoint. Over the range of operating temperatures, the mass density of the continuous fluid phase can be considered constant. It is therefore possible to eliminate the one group by considering the ratio of mass densities constant -

$$\frac{\rho_s}{\rho_l} = K_8 \quad \ldots \quad (5\text{-}4),$$

where K_8 is a constant.

It has been noted in Section 3.10 that the sand possibly smoothed out the boundary roughness. However, the antidune test series to which this dimensional analysis is directed was performed after an extended operation of sand slurries in the flume and the boundary could be considered to have a constant absolute roughness. Since the breadth was constant for all flume testing, another group can be eliminated by considering it constant -

$$\frac{\epsilon}{b} = K_9 \quad \ldots \quad (5\text{-}5),$$

where K_9 is constant.

By combining Equations (5-3), (5-4) and (5-5), we find -

$$C_s = \text{fn}\left(\frac{V^2}{gSy}, \frac{V^2}{gy}, \frac{b}{y}, \frac{Vy}{\nu}, \frac{\sqrt[3]{g\nu}\, d}{\nu}\right) \quad \ldots \quad (5\text{-}6)$$

There must be an equation of condition which describes the precise critical deposit transition. We could eliminate one independent group by solving this critical-condition equation with Equation (5-6). In this way, let us eliminate the group $\frac{V^2}{gSy}$, leaving the relation -

$$C_s = \text{fn}\left(\frac{V^2}{gy}, \frac{b}{y}, \frac{Vy}{\nu}, \frac{\sqrt[3]{g\nu}\, d}{\nu}\right) \quad \ldots \quad (5\text{-}7)$$

The group $\frac{\sqrt[3]{g\nu}\, d}{\nu}$ is a Reynolds number in terms of the particle diameter. As already noted, the diameter was constant over the range of experiments. This means that the group varies as $\left(\frac{1}{\nu}\right)^{\frac{2}{3}}$. For the data which are considered in this dimensional analysis, the range of values of ν was plus or minus 5% of the mean value. On

the basis of this very small variation, the group $\frac{\sqrt[3]{g\nu}\, d}{\nu}$ can be neglected.

These considerations lead to -

$$C_s = fn\left(\frac{V^2}{gy}, \frac{b}{y}, \frac{Vy}{\nu}\right) \quad \ldots \quad (5\text{-}8)$$

which shows only three variable dimensionless groups functionally related to concentration.

The third group $\frac{Vy}{\nu}$ is a Reynolds number in terms of depth. A parameter $R = \frac{by}{2y + b}$ is often used as a measure of length in open-channel flow, or on a rectangular channel, and the Reynolds number usually appears in the form -

$$R_e = \frac{4\,VR}{\nu} \quad \ldots \quad (5\text{-}9)$$

Re-writing Equation (5-8) -

$$C_s = fn\left(\frac{V^2}{gy}, \frac{b}{y}, \frac{4\,VR}{\nu}\right) \quad \ldots \quad (5\text{-}10)$$

As previously noted, the author could find no basic relation -

$$C_s = fn\left(\frac{V^2}{gy}\right) \quad \ldots \quad (5\text{-}11)$$

The Stanton diagram of FIG. III-15 shows the data lie in a transition zone, rather than the fully-turbulent region. With this in mind, a plot of -

$$C_s = fn\left(\frac{4\,VR}{\nu}\right) \quad \ldots \quad (5\text{-}12)$$

was prepared, which introduced some order into the data by broadly separating the antidune and clean-bed regimes. However, no clear transition between the regimes was apparent.

For the experimental data, both gravitational and viscous forces govern the flow regime. In a non-accelerated system, it seems reasonable to eliminate the inertial forces by dividing the Reynolds number by the Froude number, thus obtaining the ratio of viscous forces to gravitational forces. A plot of -

$$C_s = fn\left(\frac{4\,VR}{\nu} \cdot \frac{gy}{V^2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5\text{-}13)$$

was prepared. This plot again divided the data into groups without a clear-cut transition.

Blench (1957) has noted that the bed load-carrying capacity of a canal or river is influenced by the breadth-to-depth ratio. The author is of the opinion that this reflects the turbulence distribution and a high breadth-to-depth ratio results in a greater utilization of turbulence to suspend the solids. A plot of -

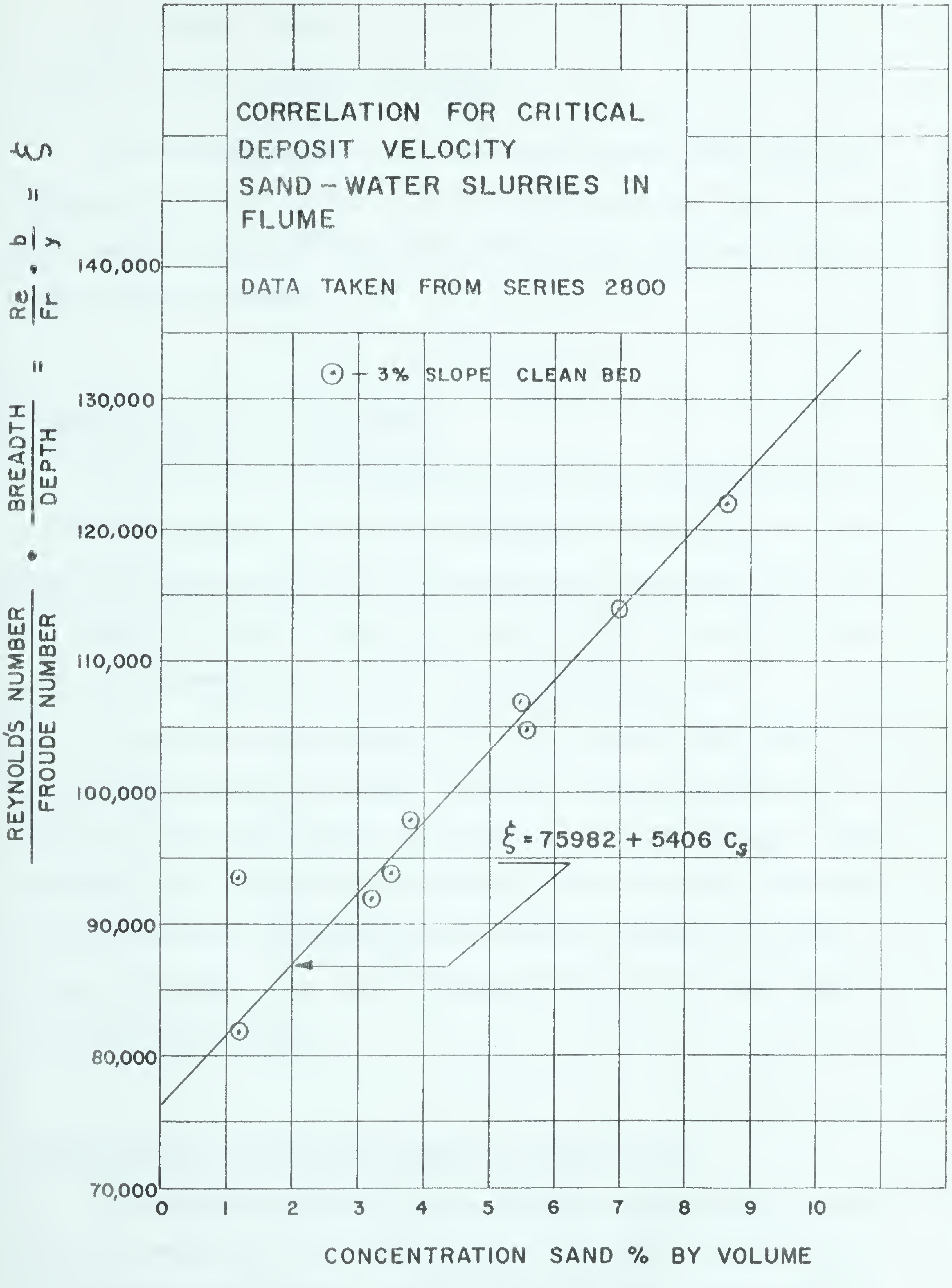
$$C_s = fn\left(\frac{4\,VR}{\nu} \cdot \frac{gy}{V^2} \cdot \frac{b}{y}\right) = fn\,(\xi) \quad \ldots\ldots\ldots \quad (5\text{-}14)$$

showed both a data grouping according to bed condition and a well-defined transition.

FIG. V-3 is a plot of Equation (5-5) for the clean bed data of the 2800 Series. These data define the critical deposit condition quite well, since the runs were specifically carried out to determine the conditions of incipient antidunes. FIG. V-3 shows an excellent linear relation. A least squares fit yielded the expression -

$$\xi = 80591 + 4656\,C_s \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5\text{-}15)$$

with a correlation coefficient of 0.914. If the one point which is off the line is excluded, the equation is -



CORRELATION FOR CRITICAL DEPOSIT VELOCITY SAND-WATER SLURRIES IN FLUME
DATA TAKEN FROM SERIES 2800
⊙ - 3% SLOPE CLEAN BED
$\xi = 75982 + 5406\ C_s$
$\frac{\text{REYNOLD'S NUMBER}}{\text{FROUDE NUMBER}} \cdot \frac{\text{BREADTH}}{\text{DEPTH}} = \frac{Re}{Fr} \cdot \frac{b}{y} = \xi$
140,000
130,000
120,000
110,000
100,000
90,000
80,000
70,000
0
1
2
3
4
5
6
7
8
9
10
CONCENTRATION SAND % BY VOLUME

FIGURE V-3

$$\xi = 75982 + 5406\ C_s \quad \text{(5-16)}$$

with a correlation coefficient of 0.995.

The remaining data of the 2800 Series plus the 2900 Series are shown on FIG. V-4, together with the plot of Equation (5-16). As can be seen, the correlation generally divides the two regimes of clean bed and bed formations.

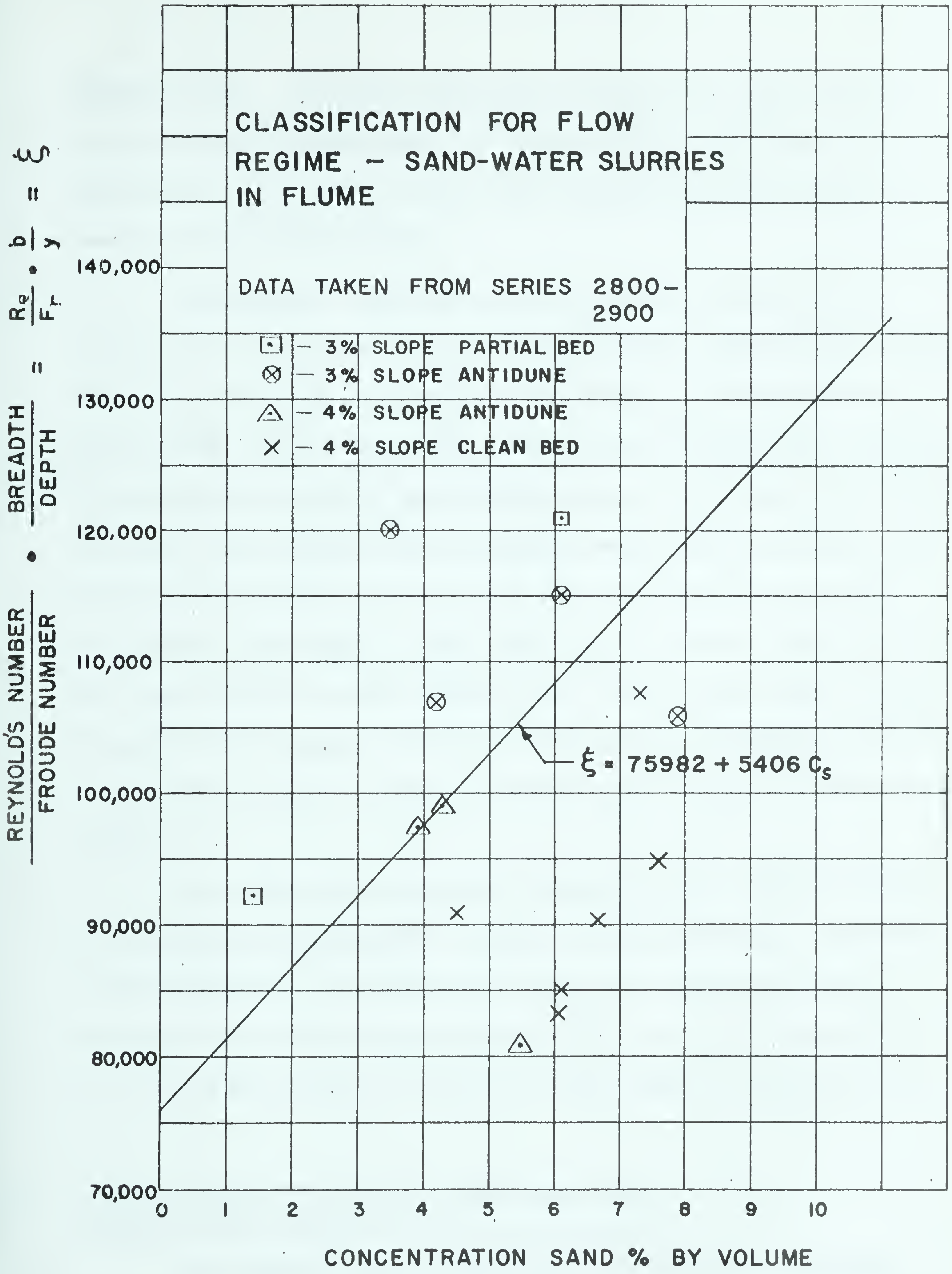
5.5 Antidunes for Fines-Sand-Water:

The fines-sand-water slurries were run by randomly building up the concentration of the solids. At a given concentration of solids, the system was throttled (i.e., discharge decreased) until a bed feature appeared. Observations were made through the transparent section of the flume and the bottom was sounded using a probe.

It was extremely difficult, due to the turbidity of the slurry, to determine the nature of the bed. However, it was established that antidunes were again the first manifestation of a bed condition. These antidunes were considerably smaller than those observed in the sand-water slurries for comparable concentration of sand at a given discharge and slope. The smaller antidunes occurred in a train rather than one large antidune.

5.6 Effect of Fines on Sand-Water Slurries in the Flume:

The author has discussed the increased sand-carrying capacity in open-channel flow due to the inclusion of the fines (Ansley, 1962). As the fines concentration was increased, at a given amount of sand and slope, the clean bed condition could be maintained at a lower



CLASSIFICATION FOR FLOW REGIME - SAND-WATER SLURRIES IN FLUME
DATA TAKEN FROM SERIES 2800-2900
- 3% SLOPE PARTIAL BED
- 3% SLOPE ANTIDUNE
- 4% SLOPE ANTIDUNE
- 4% SLOPE CLEAN BED
$\xi = 75982 + 5406\ C_s$
$\frac{\text{REYNOLD'S NUMBER}}{\text{FROUDE NUMBER}} \bullet \frac{\text{BREADTH}}{\text{DEPTH}} = \frac{R_e}{F_r} \bullet \frac{b}{y} = \xi$
140,000
130,000
120,000
110,000
100,000
90,000
80,000
70,000
0 1 2 3 4 5 6 7 8 9 10
CONCENTRATION SAND % BY VOLUME

FIGURE V-4

discharge rate. At a given slope and discharge rate, the clean bed condition could be maintained with significantly higher sand concentrations in a fluid phase of fines-water slurry than those of the sand-water slurries without fines.

Unfortunately, the data cannot be readily compared. The sand-water slurries were all carried out at flume slopes of 3% and 4%, whereas all the fines-sand-water slurry testing was done at a flume slope of 2%. An idea of the effect of fines can be obtained by comparing the maximum amounts of sand transported with and without the addition of fines. The maximum concentration of sand carried with clean bed conditions during the flume tests on sand-water slurries was 7.6%, carried at a discharge of 0.286 cubic feet per second (velocity of 5.72 feet per second) at a flume slope of 4%. With the fines added, a maximum of 10.2% sand was carried in suspension at a discharge of 0.234 cubic feet per second (velocity of 4.28 feet per second) at a flume slope of 2%.

One of the most interesting observations was, that if the fines concentration exceeded 12% by volume, a bed would form irrespective of the discharge. This phenomenon took place sufficiently often to convince the author that approximately 12% fines was the upper limit for a clean bed condition over the available range of discharge rates.

5.7 Critical Deposit Velocity for Fines-Sand-Water Slurries in the Flume :

The approach used in Section 5.5 can be used to investigate the effect of fines on the critical deposit velocity. With the inclusion of the fines, three additional variables must be included -

μ_a = Apparent absolute viscosity of the fines-water slurry in $\frac{\text{lbs. sec.}}{\text{ft.}^2}$

τ_y = Apparent yield stress of the fines-water slurry in $\frac{\text{lbs.}}{\text{ft.}^2}$

C_f = Concentration of fines by volume in %.

The physical properties of the fines mineral matter are not included specifically, since the material was considered fully dispersed and part of the continuous fluid phase.

For the fines-sand-water slurries, Equation (5-8) can be replaced by -

$$C_s = \text{fn}\left(\frac{V^2}{gy}, \frac{b}{y}, \frac{Vy}{\nu_a}, \frac{\tau_y}{V\rho_1}, C_f\right) \quad \text{(5-17)}$$

There are no reliable data for incipient antidune conditions for the fines-sand-water slurries. Several plots were prepared using both the clean bed and the antidune data of the 5700 Series, but to date the author has been unable to establish any strong correlation between the dimensionless groups of Equation (5-17).

CHAPTER VI

DISCUSSION OF RESULTS

6.1 General:

This chapter briefly summarizes the analyses outlined in CHAPTERS IV and V. The critical deposit condition correlation for flume transport of sand-water slurries is discussed and is shown to apply to pipeline transport of these same slurries.

6.2 Critical Deposit Condition for Sand-Water Slurries in the Flume:

The correlation developed in CHAPTER V for the critical deposit condition of sand-water slurries in the flume appears very promising. Although Equation (5-16) was derived from a regression analysis of the 2800 Series data (flume at 3% slope), the data for 4% flume slope of the 2900 Series do not contradict it. The 2900 Series was not run to determine the critical deposit condition, but was carried out as sand-conveyance capacity runs.

It is possible that the dimensionless group $\frac{gy}{V^2}$ of Equation (5-8) could be improved by replacing it with $\frac{gyS}{V^2}$. Thus Equation (5-14) would read -

$$C_s = fn\left(\frac{4\,VR}{\nu}, \frac{gyS}{V^2}, \frac{b}{y}\right) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (6\text{-}1)$$

Equation (6-1) would result in a comparable correlation to Equation (5-16) for the 2800 Series data, since the slope S is a constant for these data. The addition of the slope term does, however, allow

for data derived under different slope settings. It would be interesting to compare critical deposit condition data for different flume slopes.

The dimensional analysis carried out in Section 5.5 does not preclude the derivation of Equation (6-1), since the term $\frac{gyS}{V^2}$ was eliminated by algebraic substitution.

6.3 Critical Deposit Condition for Fines-Sand-Water Slurries in the Flume:

There is a good possibility that an empirical investigation of Equation (5-17) will lead to a correlation for critical deposit conditions of fines-sand-water slurries. Unfortunately, the data of the 5700 Series cannot be used for such an evaluation. However, the experimental techniques for handling fines-sand-water slurries have been consistently improved and it should now be possible to find a reliable method of experimentally determining the critical deposit condition.

6.4 Pipeline Transport of Sand-Water Slurries:

The published correlations of Durand and Newitt are widely quoted and have been generally accepted as the most reliable design criteria. The author's do not conform to the correlations over the full range of the data. Both correlations do fit the data quite well in the range of high velocities with a clean bed condition. It is the low velocity range which diverges from the correlations.

Condolios and Chapus (1963) have stated that the Durand correlation should fit the full range of data and have specifically noted that low-velocity bed formation data fit quite well. Babcock (1962) believes that the constant K_5 as noted in the literature is erroneously reported due to an arithmetic error by Worster (1954). However, the constant advocated by Babcock is approximately $\frac{K_5}{2}$, which would result in an even poorer fit of the low-velocity data of FIG. IV-6.

Newitt (1955) only intended the correlation of Equation (4-3) to fit clean pipe data. He noted that for a moving bed the correlation should be altered such that Φ is proportional to $V^{-2.0}$. The 2200 Series data do not confirm this.

Smoothing curves drawn by eye on both FIG. IV-6 and IV-7 show a fair fit to the data. FIG. VI-1 is a plot of Φ vs. $\left(\frac{R_e}{F_r}\right)$ showing that a good smoothing line can be achieved with quite a different correlation and that in this case Φ is proportional to $V^{-1.0}$. A regression analysis was carried out on thirty-eight pieces of data of the 2200 Series on sand-water slurries in the 2" pipe. The procedure used was that listed in Section D-5, which yielded the following expression

$$\Phi = 1.34 \times 10^{-} \left(\frac{R_e}{F_r}\right)^{2.0209} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6\text{-}2)$$

The correlation coefficient between Log Φ and Log$\left(\frac{R_e}{F_r}\right)$ is 0.5578, which does not indicate a good fit.

However, the smoothing line does fit the data on FIG. VI-1, noted as associated with a bed in the pipe. This suggested that a correlation of the form developed for flume critical deposit conditions could be extended to the same condition for the pipeline.

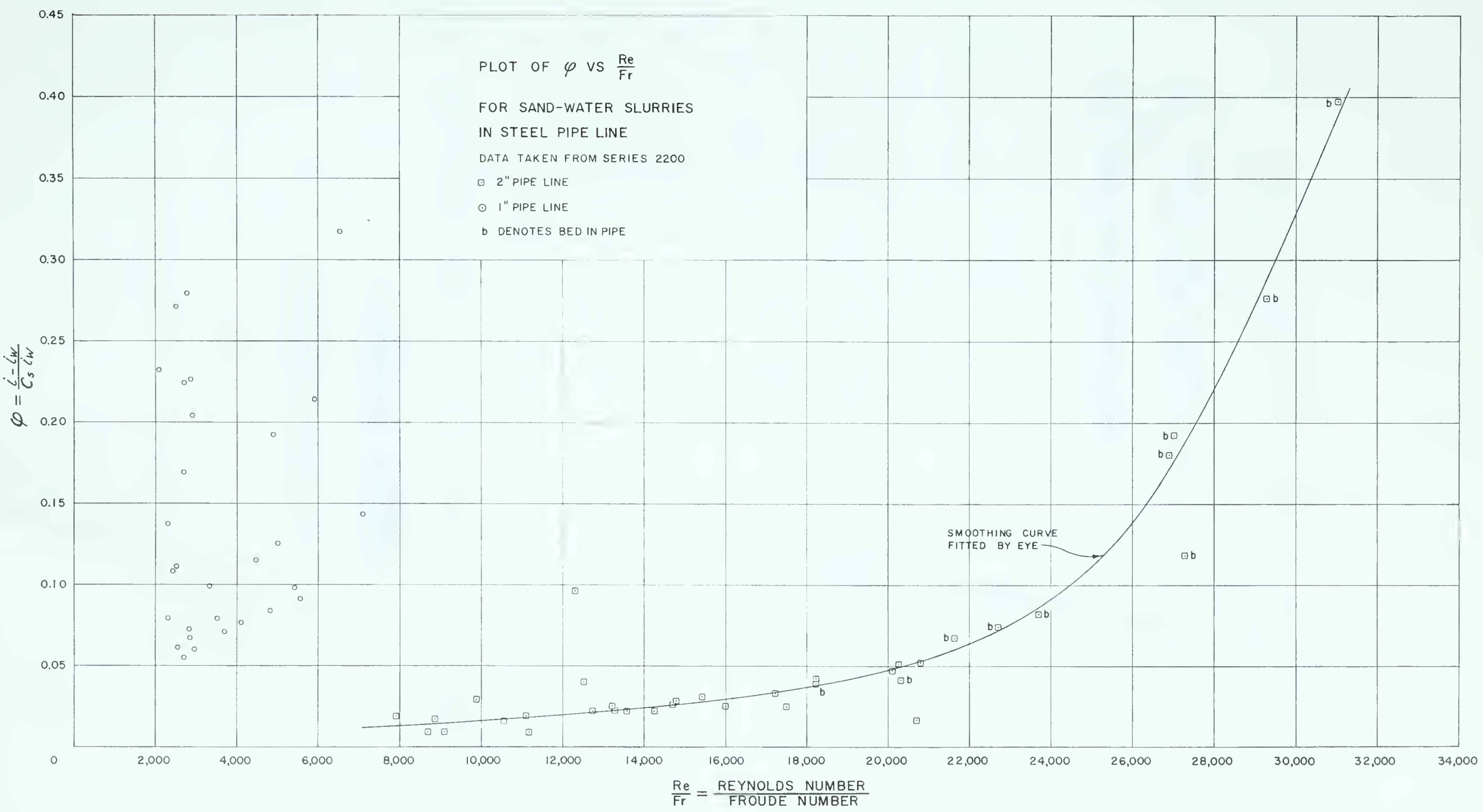
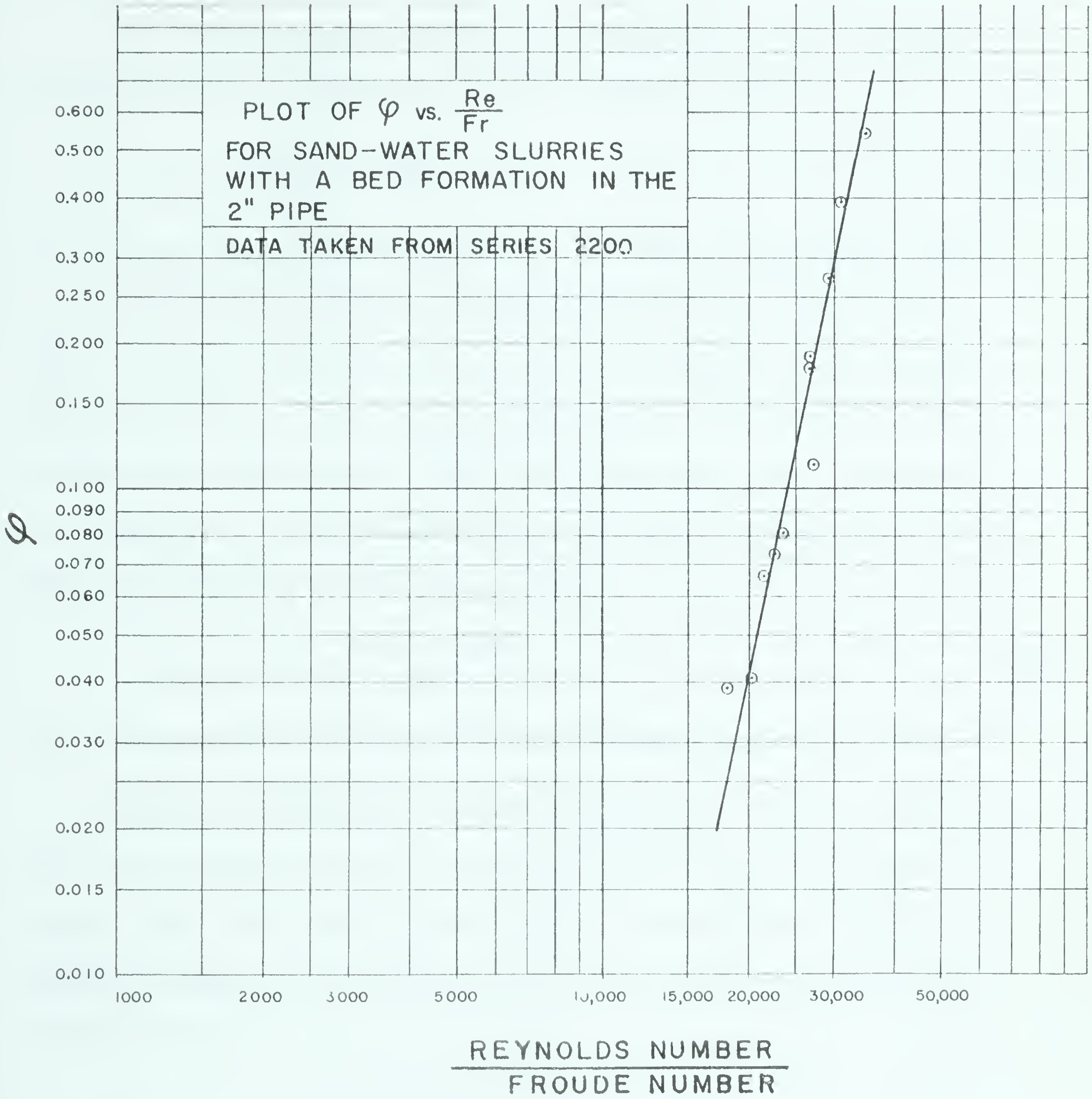

PLOT OF φ VS Re/Fr
FOR SAND-WATER SLURRIES
IN STEEL PIPE LINE
DATA TAKEN FROM SERIES 2200
2" PIPE LINE
1" PIPE LINE
b DENOTES BED IN PIPE
SMOOTHING CURVE
FITTED BY EYE
$\varphi = \frac{i - i_w}{C_s i_w}$
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
16,000
18,000
20,000
22,000
24,000
26,000
28,000
30,000
32,000
34,000
$\frac{Re}{Fr} = \frac{\text{REYNOLDS NUMBER}}{\text{FROUDE NUMBER}}$

FIGURE VI - I



PLOT OF φ vs. $\frac{Re}{Fr}$
FOR SAND-WATER SLURRIES
WITH A BED FORMATION IN THE
2" PIPE
DATA TAKEN FROM SERIES 2200
φ
0.600
0.500
0.400
0.300
0.250
0.200
0.150
0.100
0.090
0.080
0.070
0.060
0.050
0.040
0.030
0.020
0.015
0.010
1000
2000
3000
5000
10,000
15,000
20,000
30,000
50,000
REYNOLDS NUMBER / FROUDE NUMBER

FIGURE VI - 2

6.5 Critical Deposit Condition for Sand-Water Slurries in the Pipe:

The critical deposit condition for flumes was modified to suit the pipeline case. Equation (5-14) was altered to read -

$$\Phi = \text{fn}\left(\frac{VD}{\nu} \cdot \frac{gD}{V^2}\right) = \text{fn}\ \zeta \quad \ldots\ldots\ldots\ldots \quad (6\text{-}3)$$

There was no attempt made to find a term which corresponded to $\frac{b}{y}$ in Equation (5-14), since the turbulence distribution was not considered a pertinent variable in the case of a circular pipe completely filled with slurry. FIG. VI-2 is a log-log plot of Equation (6-3) for the data of the 2200 Series, which were associated with a bed deposit in the pipeline. A regression analysis performed in the manner outlined in Section D-5 yielded the expression -

$$\Phi = 2.45 \times 10^{-19} \left(\zeta\right)^{4.4794} \quad \ldots\ldots\ldots\ldots \quad (6\text{-}4)$$

with a correlation coefficient of 0.95148 between Log Φ and Log ζ.

This good correlation indicates that the same variables govern the critical deposit condition for both the pipeline and flume experimental work. The ratio of viscous forces to gravitational forces appears at least as reasonable a criterion as those put forth by other workers.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7.1 Rheological Data for Homogeneous Slurries:

The homogeneous mixtures of sludge and fines-water slurries exhibit the rheological behaviour of the Bingham Plastic model. The use of a Bingham-Reynolds number introduces a meaningful order to the data when plotted on a Stanton Diagram.

The transition zone between laminar and turbulent flow regimes for fines-water slurries in the 9 to 14% concentration range appears to occur at a Bingham-Reynolds number of approximately 50,000. This is consistent with similar observations on Bingham Plastics by Govier and Charles (1961). The high yield stress of the fines-water slurries accounts for the extension of the laminar range.

7.2 Pipeline Transport of Fluidized Solids:

The data collected during the experimental program have been compared to the published correlations of Durand and Newitt. The author's data show sharp divergences from both of these correlations at low-velocity flow conditions. The Newitt correlation fits the data best in the high velocity - clean bed flow regime. It should be noted that the experimental data used by both the author and Newitt were collected on small pipelines. The Durand experimental work was done on a wide range of pipe sizes.

7.3 Physical Description of Flume Transport of Fluidized Solids:

One of the primary objectives of the investigation was to study and describe the physical phenomena associated with flume transport of fluidized solids. Enough work has been done to convince the author that the antidune described herein is the first manifestation of a bed formation for the super-critical flow regime. The author believes that Ansley and Hebbert (1961) published the first description of the antidune phenomena associated with open-channel transport of fluidized solids.

7.4 Critical Deposit Condition in a Flume:

The firm establishment of the incipient bed formation condition is the most critical design consideration for flume transport of fluidized solids. The dimensional analysis and experimental work described herein have resulted in a satisfactory correlation for predicting the critical deposit conditions of sand-water slurries in small flumes. It is realized that the correlation in its present form cannot be extrapolated to predict deposit conditions in large flumes. The progress to date justifies considerable effort to extend the correlation for large-size flumes.

7.5 Effect of Fines on Flume Transport of Sand - Water Slurries:

The experimental data confirm that the addition of fines to a sand-water mixture increases the sand-carrying capacity of the flume. The data presented herein are a quantitative measure of this boosting effect.

The flume experiments show that there is an upper limit of fines concentration which will result in boosting the sand-carrying capacity. In the small flume, this upper limit was approximately 12% concentration of fines by volume, irrespective of flow rate. Although it has not been explained satisfactorily to date, it appears that if the fines concentration exceeds this upper limit, there is complete deposition of the sand.

7.6 Critical Deposit Conditions in the Pipeline:

The ratio of viscous forces to gravitational forces may be a meaningful parameter in pipeline transport of fluidized solids. This parameter has been shown to apply to the bed condition flow data reported herein. The preliminary analysis justifies an extension of this approach.

7.7 Recommendations:

It is recommended that -

a) additional processing of the data included herein should precede further experimental work;

b) the flume critical deposit conditions should be investigated for larger flumes at different slopes;

c) a study be carried out to determine the method in which a bed forms in a pipeline.

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LIST OF REFERENCES

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* * * * *

APPENDIX "A"

APPENDIX "A"

OPERATING LOG AND DATA PRESENTATION

A. 1 General:

This appendix discusses each individual series of runs performed on the test unit. The relative accuracy of the variables measured is discussed, as well as the procedures used to measure the variables.

The processed data are given in tabular form in APPENDIX "F." The tables are indexed in TABLE III-1 and the basis for each calculation is detailed in TABLES A-2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 and 13. A definition of some of the constants is given in TABLE A-1.

A. 2 Series 1000 - 1099:

This series of twenty-six tests using clear water was carried out to calibrate the 1" steel pipeline. Water-over-mercury manometers attached to the piezometer taps shown in FIG. II-6 were read by the operator, one by one. In an effort to compensate for the obvious surging that was taking place in the manometers, the readings were repeated several times. The hydraulic gradient was calculated over the test section between the four manometers shown in FIG. II-6. A separate hydraulic gradient was calculated for adjacent manometer taps and the three values were averaged.

The first six tests (1001 - 1006) were carried out for initial calibration. An additional ten tests (1026 - 1035) were conducted, after completion of the sand-water-slurry tests, to check the pipeline for

possible erosional effects. The final ten tests (1051 - 1060) were completed after the sludge testing. The same procedures were used in all of these individual series of tests.

The original data are not included herein. However, processed data are given in TABLE F-1 and a summary of the calculation procedures is given in TABLE A-2.

A.3 Series 1100 - 1199:

This series of tests was run on clear water through the 1" aluminum pipeline. Since the aluminum test section was installed in series with the 1" steel test section, the same twenty-six runs were carried out as for the 1000 Series. The data are reported in TABLE F-2, which is identical in format to TABLE F-1.

The inside diameter of the 1" aluminum pipeline was measured as 0.0874 feet. The test section in the aluminum pipeline can be seen in FIG. II-6. The differential manometers were read as water-over-mercury and reported in feet of water.

A.4 Series 1200 - 1299:

This series of thirteen tests was run on clear water through the initial 2" steel pipeline. The initial five tests (1201 - 1205) were conducted to calibrate the pipeline. Eight further tests (1226 - 1233) were carried out after the initial twenty runs (2201 - 2220) of the sand-water-slurry series to check for any change in the pipeline characteristics due to abrasive action of the sand.

The piezometer taps shown in FIG. II-4 were connected by tygon tubing to a series of air-over-water manometers mounted on a vertical board. The readings were taken several times to compensate for the surging. Hydraulic gradients were calculated using an average of the four hydraulic gradients obtained from the adjacent manometers in the test section of the pipeline.

The inside diameter of the 2" steel pipeline was measured at 0.1715 feet. Subsequent measurements showed no change in this figure.

The data are reported in TABLE F-3 and the calculation procedures are outlined in TABLE A-2.

A.5 Series 1300 - 1399:

This series of tests was run using clear water through the 2" aluminum pipeline. The tests were carried out concurrently with Series 1200-1299 on the test section shown in FIG. II-4. The same manometry system was used as in Series 1200-1299.

The pipe diameter of the 2" aluminum section was measured at 0.1715 feet.

The data for this series are reported in TABLE F-4. The calculation procedures followed are shown in TABLE A-2.

A.6 Series 1400 - 1499:

This series of twelve tests was carried out using clear water in the modified 2" steel pipeline. The initial seven tests (1406-1415)

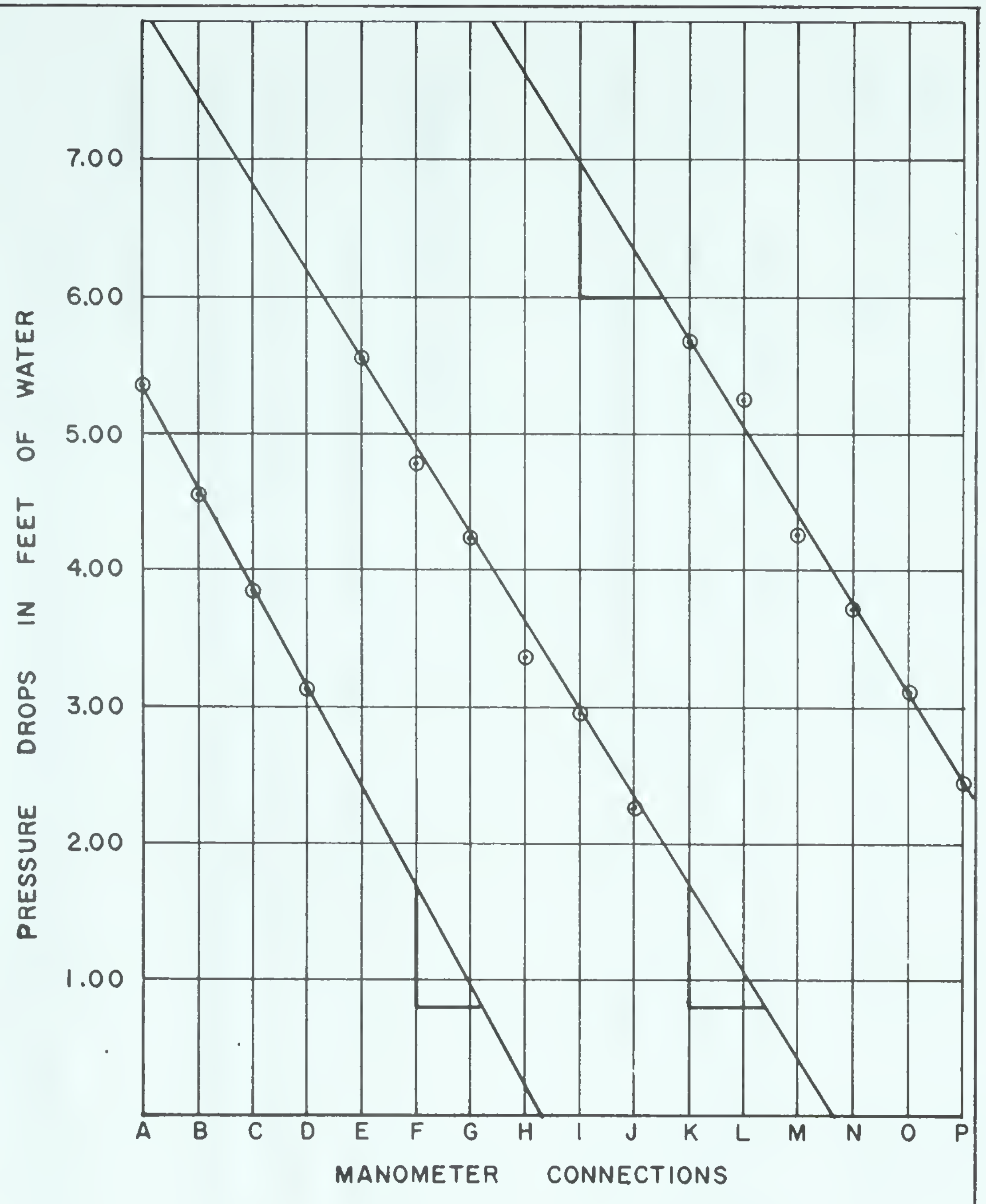
were done immediately before the commencement of the 5400 Series on fines-sand-water slurries. A further five tests (1401-1405) were carried out at the completion of the 5400 Series to check for possible changes in the pipeline.

The manometry system was completely revamped during the installation of the modified 2" steel pipeline. The piezometer taps shown in FIG. II-5 were connected by tygon tubing to the manometer system shown in FIG. II-7 and PLATE II-12. Instantaneous readings were taken on all manometers with a photograph, in the manner described by Howard (1962). The negative was mounted on a 35-mm. cardboard frame and projected on to a screen. The individual manometer readings were plotted on a prepared graph of manometer readings in feet of water vs. horizontal distance between manometer taps. A sample photograph can be seen in PLATE A-1. A typical graph is shown in FIG. A-1. A straight line was fitted by eye to the points as plotted. The slope of this straight line was measured from the graph and recorded as the hydraulic gradient in feet of water per foot of pipe.

The new manometer system performed extremely satisfactorily and eliminated the surging effects which had presented so much difficulty in the prior runs.

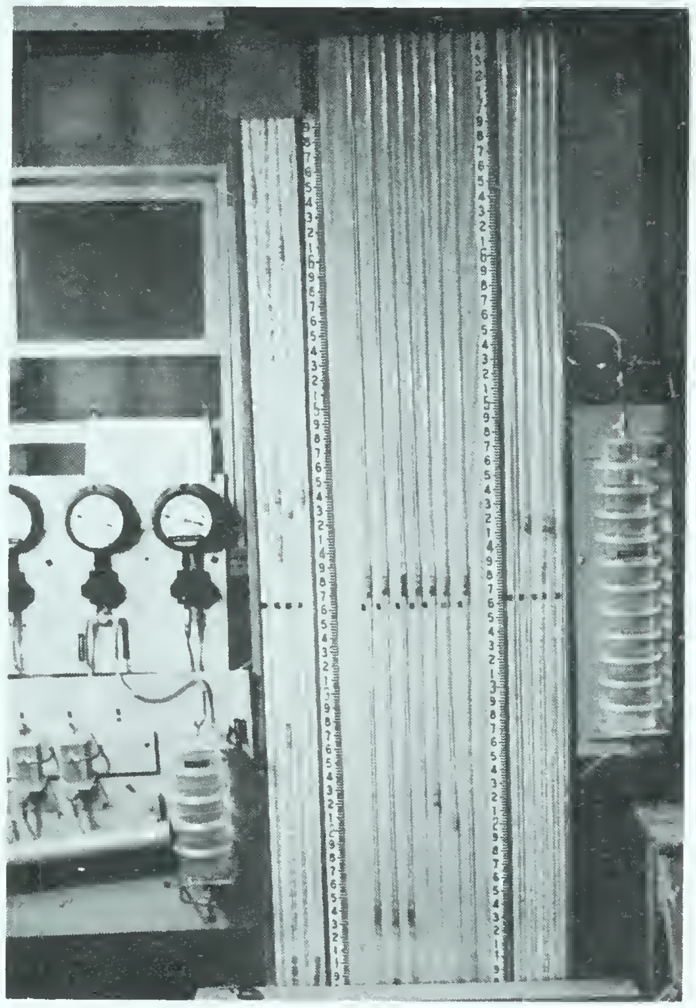
The inside diameter of the pipe was measured at 0.1715 feet.

The data are reported in TABLE F-5 and the calculation procedures used are given in TABLE A-2.



TWO INCH PIPE LINE DATA RUN Nº	DATE: RECORDED BY:
	REMARKS – CALCULATIONS: before weigh
	AVERAGE SLOPE = ΔP =

FIGURE A-1



MANOMETER BOARD

PLATE A-1

A.7 Series 1600 - 1699:

This series of eight tests was run on clear water through the flume, at a slope of 1%. The tests were carried out as calibration for the flume before any slurries were handled.

The discharge was varied by throttling the valve in the 2" pipeline on the discharge side of the Wilfley pump. The depths in the flume were measured using the probes shown in PLATE II-11. These probes were lowered until they just touched the surface of the water. The upstream and downstream depths were quite consistent during this series of tests. The depths were recorded in tenths of inches from the micrometer setting on the gauge. These were then corrected by a zero-gauge reading and converted to feet in the computer analysis of the original data. The discharge was obtained by diverting the total flow into the weigh tank, using the diversion section shown in PLATE II-10.

The width of the flume was measured at several sections and taken at an average of 0.5 feet. The data are reported in TABLE F-6 and the calculation procedures can be seen in TABLE A-3.

A.8 Series 1800 - 1899:

This series was carried out using clear water in the flume at a slope of 3%. The nine tests were conducted after completion of the 2800 Series of sand-water flume tests and immediately prior to the sludge testing.

The data were collected in the same manner and reported identically as for the 1600 Series. It should be noted, however, that the

range of discharge values is significantly less than for the 1600 Series. The data are given in TABLE F-7 and the calculation procedures are shown in TABLE A-3.

A.9 Series 2000 - 2099:

This series of thirty tests was carried out using sand-water slurry in the 1" steel pipeline. The slurry was varried in density during the testing and was reported for a range of concentrations from approximately 3% to approximately 35% by volume.

The concentrations reported in these data are unfortunately somewhat suspect. Samples were not taken for quantitative analysis. The volumetric-weight comparison in the weigh tank was used to compute a specific gravity for concentration calculations. These were augmented and roughly checked by specific gravity determinations, using a Denver balance two or three times during the run. Although the Denver balance was found to be quite inaccurate, it was used as a guide to determine if the system had reached a quasi-steady state.

The manometer readings were taken in a manner similar to those for the 1000 Series and were reported in feet of water, as read from the water-over-mercury manometers. The small orifices in the piezometer taps frequently plugged with sand particles. In such cases, the hydraulic gradients were taken over the operating piezometer taps.

At high concentrations, difficulty was encountered in keeping the slurry in the reservoir tank at a uniform consistency. This was

detected by taking slurry densities before and after the weighing period of the run. For the tests with concentrations above 30% by volume, the reservoir tank was not used. Instead, a small weigh was taken and the head in the sump tank was allowed to fall only about 4 inches. This resulted in a short weigh period and a larger percentage of error in discharge determination.

The manometers were read before and after the weigh period and the values were averaged to compensate for any imbalance introduced by the weighing procedure. The data are reported in TABLE F-8 and the calculation procedures are listed in TABLE A-4.

A.10 Series 2100 - 2199:

This series was carried out using a sand-water slurry in the 1" aluminum pipe. Although these tests were not conducted concurrently with the 2000 Series, the data were collected in identical fashion and are reported in TABLE F-9, in the same format as described in TABLE A-4.

A.11 Series 2200 - 2299:

This series of thirty-eight tests was run on sand-water slurry through the initial 2" steel pipeline. The range of concentrations of the slurries was from approximately 1% to approximately 34%. The inspection section of the 2" pipeline was used to ascertain the bed condition, if any, at high concentrations. It should be noted that many of the runs exhibited a sand bed in the bottom of the pipe. Runs 2201

to 2220, which were all 7.5% concentration or less, employed both the pipeline and the return flume. For higher concentrations, as in Runs 2221-2239, a return pipeline was necessary due to deposit of sand in the return flume.

The data are reported in TABLE F-10 and the calculation procedures are shown in TABLE A-4.

A.12 Series 2300 - 2399:

This series was run with sand-water slurry in the 2" aluminum pipeline. These runs were done concurrently with the 2200 Series. The data are reported in TABLE F-11 and the calculation procedures are shown in TABLE A-4.

A.13 Series 2800 - 2899:

This series was carried out using a sand-water slurry in the flume at 3% slope. These runs can be related to the 2300 Series by examining the date and discharge, since the pipeline discharge was returned to the weigh tank via the flume.

Seventeen runs were made at a range of concentrations from 1% to 7% sand-by-volume.

During the runs it was often noticed that there was a bed condition in the flume. A classification system set up to describe this bed condition was delineated as follows:

1) Antidune
2) Clean bed
3) Jerking bed
4) Partial bed.

The clean bed condition was the desired operating condition, in which the bed was running clean with no material in any bed form. The anti-dune condition was the first manifestation of a bed condition. The jerking bed condition, as observed through the plexiglass bottom of the flume, was defined as that condition when sand grains were moving over the flume bottom as a thin sheet which remained stationary for short intervals and then moved again. The partial bed described a condition when a stationary bed was formed in a corner of the flume and extended over a considerable length of the flume. In some instances, although the flume had a complete bed, it was still classified as partial. Unfortunately, the description of the bed condition was somewhat arbitrary and, in the case of many runs, it was difficult to differentiate between an antidune and a partial bed condition.

The data are reported in TABLE F-12 and the calculation procedures are noted in TABLE A-5.

A.14 Series 2900 - 2999:

This series of tests was carried out using sand-water slurry in the flume at a 4% slope. Nine runs were made after completion of the 2800 Series. The data are presented in TABLE F-13 and the calculation procedures are outlined in TABLE A-5.

A.15 Series 3200 - 3299:

This series of tests was run using sludge in the initial 2" steel pipeline. Seventy-nine tests were carried out over a range of concentrations from approximately 1% to $2\frac{1}{2}$% solids-by-volume.

The hydraulic gradients were derived in the manner described for Series 2000. It should be noted that all the hydraulic gradients are expressed in feet of water and that the manometers were read in feet of water.

The sludge was considered a non-Newtonian fluid and as such a rheological investigation was carried out. The apparent kinematic viscosity of the sludge was taken from FIG. III-9.

The sludge concentrations were determined from grab samples in the sump, using the procedure described in Section 2.3 and calculated as outlined in TABLE A-6.

The data are recorded in TABLE F-14 and the calculation procedures are outlined in TABLE A-6.

A.16 Series 3600 - 3699:

This series of twenty-four tests was run using sludge in the flume on a 1% slope, over a range of concentrations from approximately 0.8% to 2.7% . These tests can be related to the 3200 Series by comparing the dates and discharge data.

There were no antidune or other bed formations during this series of flume tests. The sludge presented no difficulty in the flume operation and there were no apparent indications of an anomalous behaviour due to the non-Newtonian characteristics of the fluid.

The data are reported in TABLE F-15 and the calculation procedures are given in TABLE A-7.

A.17 Series 3700 - 3799:

This series of tests was carried out using sludge in the flume at 2% slope. Forty-two tests were made over a range of concentrations of approximately 0.8% to 3% by volume. Many of these tests can be correlated to the 3200 Series by a comparison of date and discharge data.

The data are reported in TABLE F-16 and the calculation procedures are outlined in TABLE A-7.

A.18 Series 3800 - 3899:

This series of tests was run using sludge in the flume at 3% slope. Thirty-four tests were made over a range of concentrations of approximately 0.8% to 2.9% by volume. This series of tests can also be compared to the 3200 Series, using the date and discharge data as identification.

The data are reported in TABLE F-17 and the calculation procedures are outlined in TABLE A-7.

A.19 Series 3900 - 3999:

These tests were carried out using sludge in the flume at 4% slope. Forty-six tests were made through a range of concentrations of approximately 0.8% to 3% by volume. Some of these tests can be correlated to the 3200 Series by comparing dates and discharge data.

The data are reported in TABLE F-18 and the calculation procedures are listed in TABLE A-7.

A.20 Series 4200 - 4299:

This series of tests was conducted using a fines-water slurry in the initial 2" steel pipeline. Fifty-five tests were made over a range of concentrations of approximately 2% to 18% by volume. The series was run as a complete set of tests over a period of about two weeks.

The slurry concentration was built up by shovelling pulverized fines into the sump tank and continuously recirculating until the material was well dispersed and the slurry became a homogeneous fluid phase. At the end of a day's testing, the material was stored either in the reservoir tank or in the weigh tank. It was noted that the solids readily settled overnight and a fairly clear supernatant liquid appeared above a well-defined interface. Providing there was sufficient material available in the system for testing, it was a fairly simple matter to increase the concentration by evaporation of the water. No difficulty was encountered in cleaning out the tanks and no tendency for the solids to build up in the corners during this series of tests.

The manometers were read on the vertical board as before and the surging effects were very marked. The tygon tubing was frequently plugged due to settling of the fines in the lines overnight. The manometry instrumentation became very difficult to operate during this series of tests. The manometer readings were again taken in feet of water and the hydraulic gradients are reported in feet of water per foot of pipe.

The data are reported in TABLE F-19 and the calculation procedures are outlined in TABLE A-8.

A.21 Series 4700 - 4799:

This series of tests was made using a fines-water slurry in the flume on a 2% slope. Forty-eight tests are reported over a range of concentrations of approximately 2% to 13% by volume. Some of these tests can be correlated to the 4200 Series by using the date and discharge data as identification.

The non-Newtonian characteristics of the fluid became extremely evident in the flume tests, particularly at high concentrations of fines. The depth measurements are quite inaccurate, in that waves ran down the surface of the flume. These waves tended to increase in amplitude with an increase in concentration of fines. A fair degree of operator skill was involved in measuring the depth. At the end of a series of runs, the flume would not completely drain. The material would stay in place to a depth depending upon the concentration of the slurry: the higher the concentration the deeper the material would stay in the flume without draining. The author believes that the yield stress of the non-Newtonian fluid contributed both to the waves and to this non-draining feature. Sufficient depth was required in the headbox of the flume before yield stress in that area could be overcome and a wave would run down the flume. Aside from complicating the depth measurements, as already mentioned, the discharge measurements were rather tricky since the flume emptied into the weigh tank in a periodic surge with no discharge at all between the surges. The period of the surges was of the order of several seconds and increased with an increase in concentration of the slurry.

The bed condition is reported as clean bed for all the runs. By visual inspection the fluid seemed homogeneous at all concentrations tested.

The data are reported in TABLE F-20 and the calculation procedures are given in TABLE A-9.

A.22 Series 4900 - 4999:

This series was run as a fines-water slurry in the flume at a 4% slope. Eighteen tests were run over a range of concentrations of approximately 14% to 19% . These tests may be correlated to the 4200 Series by comparison of date and discharge data.

It should be noted that all these tests were carried out on very high-concentration slurries and that the depth and discharge data are quite rough due to surging in the flume. The increased slope decreased the wave heights and the depth of material that would remain in the flume after draining.

The data are reported in TABLE F-21 and the calculation procedures are outlined in TABLE A-9.

A. 23 Series 5400 - 5499:

This series was carried out using a fines-sand-water slurry in the modified 2" steel pipeline. Fifty-three tests were run in one block of testing over a range of approximately 6% to 16% by volume of fines and a range of 0% to 11% by volume of sand.

The revamped manometer system described by Howard (1962) worked extremely well during this testing. Although the lines plugged up, the back-pressure system could be used to clean the lines each morning and thus during the bulk of the testing program all the manometer leads were in use.

It should be noted that the testing took place over a period of approximately three months. This rather lengthy period was due to several reasons, but could generally be attributed to the difficulty in handling the very heavy three-component mixture. When the flume was used, a bed could be formed which had to be dug out by hand, thus losing two or three days' testing time. The procedures followed to determine the mixture components, as described in Section 2.3, were quite laborious and time-consuming.

With the inclusion of the new manometer system and the analysis of grab samples, the data are considered quite reliable.

The data are reported in TABLE F-22 and the calculation procedures are outlined in TABLE A-10.

A.24 Series 5700 - 5799:

This series of tests was carried out on a fines-sand-water slurry in the flume at a slope of 2%. Eighty-four tests were made in this series and many of them can be correlated with the 5400 Series by comparing dates and discharge data.

A great deal of difficulty was encountered during the testing. In order to achieve an antidune or partial bed condition, the flow

was throttled using the valve on the discharge side of the Wilfley pump. Unfortunately, in many instances of high-concentration testing, an antidune would commence and almost immediately the whole bed would be covered with solids. It was found that even by circulating water with both the Wilfley and the Fairbanks pumps, it was impossible to re-slurry the material and pick it up off the bed. This meant that the entire flume had to be dug out by hand and flushed by hose. It can be seen in the data that the bed was noted for most of the tests as either "jerking bed" or "partial bed." This was due to the difficulty in isolating an individual antidune or train of antidunes. The surging in the flume still took place, but was not as evident as in the fines-water-slurry testing. The high yield stress of the homogeneous fluid phase resulted in considerable material remaining in the flume after draining.

The data are reported in TABLE F-23 and the calculation procedures are outlined in TABLE A-11.

TABLE A-1

g	=	Acceleration due to gravity at Edmonton = 32.2 ft./sec.^{2}
D	=	Measured internal pipe diameter in feet.
D_1	=	0.0874 ft. for 1 Schedule 40 steel pipeline.
D_2	=	0.0874 ft. for 1 aluminum pipeline.
D_3	=	0.1715 ft. for 2 Schedule 40 steel pipeline.
D_4	=	0.1715 ft. for 2 aluminum pipeline.
b	=	Mean breadth of flume = 0.50 ft.
γ_w	=	Specific weight of water = 62.4 lbs./ft.^{3}
γ_s	=	Specific weight of sand = 165.4 lbs./ft.^{3}
γ_f	=	Specific weight of fines = 169.1 lbs./ft.^{3}
γ_{sl}	=	Specific weight of sludge solids = 169.1 lbs./ft.^{3}
G_s	=	Specific gravity of sand = 2.65
G_f	=	Specific gravity of fines = 2.71
G_{sl}	=	Specific gravity of sludge solids = 2.71
ρ_w	=	Mass density of water = 1.94 slugs/ft.^{3}
ρ_s	=	Mass density of sand = 5.14 slugs/ft.^{3}
ρ_f	=	Mass density of fines = 5.26 slugs/ft.^{3}
ρ_{sl}	=	Mass density of sludge solids = 5.26 slugs/ft.^{3}

TABLE A - 2

Data Reported for Series:

1000 - 1099
1100 - 1199
1200 - 1299
1300 - 1399
1400 - 1499

Run N°: Serial number of test.

Date: Date the run was carried out on unit.

Kinematic Viscosity in $Ft.^2/Sec.$: ν = Value taken from Fig. 1.10, Streeter (1961), using temperatures recorded in °F. on thermometer immersed in sump tank.

Discharge in $Ft.^3/Sec.$: $$Q = \frac{\text{Weight of water collected in weigh tank}}{\text{Specific Wt. of water} \times \text{Time interval}}$$

Velocity: $$V = \frac{Q}{\frac{\pi D^2}{4}}$$

Hydraulic Gradient in $\frac{\text{feet of water}}{\text{foot of pipe}}$: i_w = Manometer differentials over test section

Reynolds Number: $$R_e = \frac{V D}{\nu}$$

Friction Factor: $$f = \frac{2 i_w D g}{V^2}$$

TABLE A-3

Data Reported for Series: 1600 - 1699
1800 - 1899

Run N°:	Serial number of test.	
Date:	Date the run was carried out on unit.	
Temperature in °F:	Value recorded on thermometer immersed in sump tank.	
Kinematic Viscosity in $Ft.^2/Sec.$:	ν =	Value taken from Fig. 1.10, Streeter (1961), using temperature above.
Discharge in $Ft.^3/Sec.$:	$Q = \dfrac{\text{Weight of water collected in weigh tank}}{\text{Specific Wt. of water} \times \text{Time interval}}$	
Velocity in Ft./Sec.:	$V = \dfrac{Q}{by}$	
Hydraulic Radius in Ft.:	$R = \dfrac{by}{2y+b}$	
Breadth-to-Depth Ratio:	$\dfrac{b}{y}$	
Reynolds Number:	$R_e = \dfrac{4RV}{\nu}$	
Friction Factor:	$f = \dfrac{8gRS}{V^2}$	
Manning's "n":	$n = \dfrac{1.486}{V} R^{2/3} S^{1/2}$	
Bed Factor in $Ft./Sec.^2$:	$F_b = \dfrac{V^2}{y}$	
Side Factor in $Ft.^2/Sec.^3$:	$F_s = \dfrac{V^3}{b}$	
King's Constant:	$C_k = \dfrac{V^2}{gyS} \times \left(\dfrac{\nu}{Vb}\right)^{\frac{1}{4}}$	
Shear Velocity in Ft./Sec.:	$U_* = \sqrt{gyS}$	
Velocity Ratio:	$\dfrac{U_*}{V}$	

TABLE A-4

Data Reported for Series:

2000 - 2099
2100 - 2199
2200 - 2299
2300 - 2399

Run N°: Serial number of test.

Date: Date the run was carried out on unit.

Concentration of Sand % by Volume:
$$C_s = \frac{\text{Volume of sand}}{\text{Volume of (sand + water)}} \times 100\%$$
$$= 100 \left[\frac{\text{Weight in weigh tank - (Volume in weigh tank)}\ \gamma_w}{\text{(Volume in weigh tank)}\ (\gamma_s - \gamma_w)} \right]$$

Kinematic Viscosity in Ft.²/Sec.: ν = Value taken from Fig. 1.10, Streeter (1961), using temperatures recorded in °F on thermometer immersed in sump tank.

Discharge in Ft.³/Sec.:
$$Q = \frac{\text{Volume of slurry in weigh tank}}{\text{Time interval}}$$

Velocity:
$$V = \frac{Q}{\frac{\pi D^2}{4}}$$

Hydraulic Gradient in $\frac{\text{feet of water}}{\text{foot of pipe}}$: i_w = Manometer differentials over test section.

Reynolds Number:
$$R_e = \frac{VD}{\nu}$$

Friction Factor:
$$f = \frac{2\, i_w\, Dg}{V^2}$$

TABLE A - 5

Data Reported for Series:

2800 - 2899
2900 - 2999

Run N°:	Serial number of test.
Date:	Date the run was carried out on unit.
Bed Type:	1) Antidune 2) Clean bed 3) Jerking bed 4) Partial bed.
Concentration Sand % by Volume:	$C_s = \frac{\text{Volume of sand}}{\text{Volume of (sand + water)}} \times 100\%$ $= 100 \left[\frac{\text{Weight in weigh tank - (Volume in weigh tank)} \gamma_w}{\text{(Volume in weigh tank)} (\gamma_s - \gamma_w)} \right]$
Kinematic Viscosity in Ft.²/Sec.:	ν - Value taken from Fig. 1.10, Streeter (1961), using temperatures recorded in °F on thermometer immersed in weigh tank.
Discharge in Ft.³/Sec.:	$Q = \frac{\text{Volume of slurry in weigh tank}}{\text{Time interval}}$
Velocity in Ft./Sec.:	$V = \frac{Q}{by}$
Upstream Depth in Ft.:	Depth of fluid in flume at upstream gauge.
Downstream Depth in Ft.:	Depth of fluid in flume at downstream gauge.
Mean Depth in Ft.:	y = Arithmetic average of upstream and downstream depths.
Hydraulic Radius in Ft.:	$R = \frac{by}{2y + b}$
Breadth-to-Depth Ratio:	$\frac{b}{y}$
Froude Number:	$F_r = \frac{V^2}{gy}$
Reynolds Number in Terms of Water Viscosity:	$R_e = \frac{4RV}{\nu}$
Friction Factor:	$f = \frac{8g\,RS}{V^2}$
Manning's "n":	$n = \frac{1.486}{V} R^{2/3} S^{1/2}$
King's Constant:	$C_k = \frac{V^2}{gyS} \times \left(\frac{\nu}{Vb}\right)$
Shear Velocity in Ft./Sec.:	$U_* = \sqrt{gyS}$
Velocity Ratio:	$\frac{U_*}{V}$

TABLE A-6

Data Reported for Series: 3200 - 3299

Run N°: Serial number of test.

Date: Date the run was carried out on unit.

Concentration Sludge % by Volume: $C_{sl} = \frac{\text{Volume of sludge solids}}{\text{Volume of sludge}} \times 100\,\%$

$$= 100 \left[\frac{\text{Weight of sludge solids in sample}}{\gamma_{sl}\ \text{(Volume of sample)}} \right]$$

Apparent Kinematic Viscosity of Sludge in Ft.²/Sec.: Taken from FIG. III-9.

Discharge in Ft.³/Sec.: $Q = \frac{\text{Volume of sludge in weigh tank}}{\text{Time interval}}$

Velocity: $V = \frac{Q}{\frac{\pi D^2}{4}}$

Hydraulic Gradient in $\frac{\text{feet of water}}{\text{foot of pipe}}$: i_w = Manometer differentials over test section.

Bingham-Reynolds Number in Terms of Sludge Viscosity: $BR_e = \frac{VD}{\nu_a}$

Friction Factor: $f = \frac{2\, i_w D g}{V^2}$

Kinematic Viscosity of Water at Operating Temperature in Ft.²/Sec.: ν = Value taken from Fig. 1.10, Streeter (1961), using temperature recorded in °F on thermometer immersed in weigh tank.

TABLE A-7

Data Reported for Series:	3600 - 3699 3700 - 3799 3800 - 3899 3900 - 3999
Run N°:	Serial number of test.
Date:	Date the run was carried out on unit.
Bed Type:	1) Antidune 2) Clean bed 3) Jerking bed 4) Partial bed.
Temperature, °F:	Temperature recorded on thermometer immersed in sump tank.
Concentration Sludge % by Volume:	$C_{sl} = \frac{\text{Volume of sludge solids}}{\text{Volume of sludge}} \times 100\ \%$ $= 100 \left[\frac{\text{Weight of sludge solids in sample}}{\gamma_{sl}\ (\text{Volume of sample})} \right]$
Apparent Kinematic Viscosity of Sludge in Ft.²/Sec.:	Taken from FIG. III-9.
Kinematic Viscosity of Water at Operating Temperature in Ft.²/Sec.:	ν = Value taken from Fig. 1.10, Streeter (1961), using temperature above.
Sludge Specific Gravity from Sample:	$G_{sl} = \frac{\text{Weight of Sample}}{(\text{Volume of sample})\ \gamma_w}$
Discharge in Ft.³/Sec.:	$Q = \frac{\text{Volume of sludge in weigh tank}}{\text{Time interval}}$
Velocity:	$V = \frac{Q}{by}$
Upstream Depth in Ft.:	Depth of fluid in flume at upstream gauge.
Downstream Depth in Ft.:	Depth of fluid in flume at downstream gauge.
Mean Depth in Ft.:	y = Arithmetic average of upstream and downstream depths.
Hydraulic Radius in Ft.:	$R = \frac{by}{2y + b}$
Breadth-to-Depth Ratio:	$\frac{b}{y}$
Froude Number:	$F_r = \frac{V^2}{gy}$
Reynolds Number in Terms of Water Viscosity:	$R_e = \frac{4RV}{\nu}$
Bingham-Reynolds Number in Terms of Sludge Viscosity:	$BR_e = \frac{4RV}{\nu_a}$
Friction Factor:	$f = \frac{8gRS}{V^2}$
Manning's "n":	$n = \frac{1.486}{V} R^{2/3} S^{\frac{1}{2}}$
King's Constant:	$C_k = \frac{V^2}{gyS} \times \left(\frac{\nu}{Vb}\right)^{\frac{1}{4}}$
King's Constant in Terms of Sludge Viscosity:	$BC_k = \frac{V^2}{gyS} \times \left(\frac{\nu_a}{Vb}\right)^{\frac{1}{4}}$
Shear Velocity in Ft./Sec.:	$U_* = \sqrt{gyS}$
Velocity Ratio:	$\frac{U_*}{V}$

TABLE A-8

Data Reported for Series: 4200 - 4299

Run N°:		Serial number of test.
Date:		Date the run was carried out on unit.
Concentration Fines % by Volume:	C_f	$= 100 \dfrac{(\text{Volume of fines})}{\text{Volume of slurry}} = 100 \dfrac{(\text{Weight of fines in sample})}{(\text{Volume of sample})\ \gamma_f}$
Apparent Kinematic Viscosity of Fines-Water Slurry in Ft.²/Sec.:	ν_a	= Value taken from FIG. III-10.
Discharge in Ft.³/Sec.:	Q	$= \dfrac{\text{Volume of slurry in weigh tank}}{\text{Time interval}}$
Velocity:	V	$= \dfrac{Q}{\frac{\pi D^2}{4}}$
Hydraulic Gradient in $\frac{\text{feet of water}}{\text{foot of pipe}}$:	i_w	= Manometer differentials over test section.
Bingham-Reynolds Number in Terms of Slurry Viscosity:	BR_e	$= \dfrac{VD}{\nu_a}$
Friction Factor:	f	$= \dfrac{2 i_w Dg}{V^2}$

TABLE A-9

Data Reported for Series: 4700 - 4799
4900 - 4999

Run N°: Serial number of test.

Date: Date the run was carried out on unit.

Bed Type:
1) Antidune
2) Clean bed
3) Jerking bed
4) Partial bed.

Temperature in °F: Recorded on thermometer immersed in sump tank.

Concentration Fines % by Volume: $C_f = 100 \dfrac{(\text{Volume of fines})}{\text{Volume of slurry}} = 100 \dfrac{(\text{Weight of fines in sample})}{(\text{Volume of sample})\ \gamma_f}$

Apparent Kinematic Viscosity of Fines-Water Slurry in Ft.²/Sec.: ν_a = Value taken from FIG. III-10.

Kinematic Viscosity of Water at Operating Temperature, Ft.²/Sec.: ν = Value taken from Fig. 1.10, Streeter (1961), using temperature above.

Specific Gravity of Slurry from Sample: $G_1 = \dfrac{\text{Weight of sample}}{(\text{Volume of sample})\ \gamma_w}$

Specific Gravity of Slurry from Weigh Tank: $\dfrac{\text{Weight in weigh tank}}{\gamma_w\ (\text{Volume in weigh tank})}$

Discharge in Ft.³/Sec.: $Q = \dfrac{\text{Volume of slurry in weigh tank}}{\text{Time interval}}$

Velocity: $V = \dfrac{Q}{by}$

Upstream Depth in Ft.: Depth of fluid in flume at upstream gauge.

Downstream Depth in Ft.: Depth of fluid in flume at downstream gauge.

Mean Depth in Ft.: y = Arithmetic average of upstream and downstream depths.

Reynolds Number in Terms of Water Viscosity: $R_e = \dfrac{4RV}{\nu}$

Bingham-Reynolds Number in Terms of Slurry Viscosity: $BR_e = \dfrac{4RV}{\nu_a}$

Friction Factor: $f = \dfrac{8gRS}{V^2}$

Manning's "n": $n = \dfrac{1.486}{V} R^{2/3} S^{1/2}$

King's Constant in Terms of Water Viscosity: $C_k = \dfrac{V^2}{gyS} \times \left(\dfrac{\nu}{Vb}\right)^{\frac{1}{4}}$

King's Constant in Terms of Slurry Viscosity: $BC_k = \dfrac{V^2}{gyS} \times \left(\dfrac{\nu_a}{Vb}\right)^{\frac{1}{4}}$

Shear Velocity in Ft./Sec.: $U_* = \sqrt{gyS}$

Velocity Ratio: $\dfrac{U_*}{V}$

TABLE A-10

Data Reported for Series: 5400 - 5499

Run N°:		Serial number of test.
Date:		Date the run was carried out on unit.
Concentration Fines % by Volume:	C_f	$= 100 \frac{\text{(Volume of fines)}}{\text{Volume of mixture}} = 100 \frac{\text{(Weight of fines in sample)}}{\text{(Volume of sample) } \gamma_f}$
Concentration Sand % by Volume:	C_s	$= 100 \frac{\text{(Volume of sand)}}{\text{Volume of mixture}} = 100 \frac{\text{(Weight of sand in sample)}}{\text{(Volume of sample) } \gamma_s}$
Apparent Kinematic Viscosity of Fines-Water Slurry in $Ft.^2/Sec.$:	ν_a	= Value taken from FIG. III-10.
Discharge in $Ft.^3/Sec.$:	Q	$= \frac{\text{Volume of slurry in weigh tank}}{\text{Time interval}}$
Velocity in Ft./Sec.:	V	$= \frac{Q}{\frac{\pi D^2}{4}}$
Hydraulic Gradient in $\frac{\text{feet of water}}{\text{foot of pipe}}$:	i_w	= Manometer differentials over test section.
Bingham-Reynolds Number in Terms of Fines-Water-Slurry Viscosity:	BR_e	$= \frac{VD}{\nu_a}$
Friction Factor:	f	$= \frac{2\, i_w\, Dg}{V_2}$
Kinematic Viscosity of Water at Operating Temperature, $Ft.^2/Sec.$:	ν	= Value taken from Fig. 1.10, Streeter (1961), using temperature recorded on thermometer immersed in weigh tank (°F).

TABLE A-11

Data Reported for Series:	5700 - 5799
Run N°:	Serial number of test.
Date:	Date the run was carried out on unit.
Bed Type:	1) Antidune 2) Clean bed 3) Jerking bed 4) Partial bed.
Temperature, °F:	Recorded on thermometer immersed in sump tank.
Concentration Fines % by Volume:	$C_f = 100 \dfrac{(\text{Volume of fines})}{\text{Volume of mixture}} = 100 \dfrac{(\text{Weight of fines in sample})}{(\text{Volume of sample})\ \gamma_f}$
Concentration Sand % by Volume:	$C_s = 100 \dfrac{(\text{Volume of sand})}{\text{Volume of mixture}} = 100 \dfrac{(\text{Weight of sand in sample})}{(\text{Volume of sample})\ \gamma_s}$
Apparent Kinematic Viscosity of Fines-Water Slurry in Ft.²/Sec.:	ν_a = Value taken from FIG. III-10.
Specific Gravity of Mixture from Sample:	$G_m = \dfrac{(\text{Weight of sample})}{(\text{Volume of sample})\ \gamma_w}$
Specific Gravity of Mixture from Weigh Tank:	$\dfrac{(\text{Weight of weigh tank})}{(\text{Volume of weigh tank})\ \gamma_w}$
Discharge in Ft.³/Sec.:	$Q = \dfrac{\text{Volume in weigh tank}}{\text{Time interval}}$
Velocity:	$V = \dfrac{Q}{by}$
Upstream Depth in Ft.:	Depth of fluid in flume at upstream gauge.
Downstream Depth in Ft.:	Depth of fluid in flume at downstream gauge.
Mean Depth in Ft.:	y = Arithmetic average of upstream and downstream depths.
Hydraulic Radius in Ft.:	$R = \dfrac{by}{2y + b}$
Breadth-to-Depth Ratio:	$\dfrac{b}{y}$
Reynolds Number in Terms of Water Viscosity:	$R_e = \dfrac{4RV}{\nu}$
Bingham-Reynolds Number in Terms of Slurry Viscosity:	$BR_e = \dfrac{4RV}{\nu_a}$
Friction Factor:	$f = \dfrac{8gRS}{V^2}$
Manning's "n":	$n = \dfrac{1.486}{V} R^{2/3} S^{1/2}$
King's Constant in Terms of Water Viscosity:	$C_k = \dfrac{V^2}{gyS} \times \left(\dfrac{\nu}{Vb}\right)^{\frac{1}{4}}$
King's Constant in Terms of Slurry Viscosity:	$BC_k = \dfrac{V^2}{gyS} \times \left(\dfrac{\nu_a}{Vb}\right)^{\frac{1}{4}}$
Shear Velocity in Ft./Sec.:	$U_* = \sqrt{gyS}$
Velocity Ratio:	$\dfrac{U_*}{V}$

APPENDIX "B"

APPENDIX "B"

ACCURACY OF EXPERIMENTAL RESULTS

B.1 General:

It has been pointed out that the accuracy of the experimental data was improved as the program proceeded. The main difficulties which had to be overcome were: surging in the manometry system, sump drawdown effects on discharge determination, analysis of the slurry components and depth measurements in the flume.

As will be shown in the ensuing sections, the most accurate data were obtained during the 5400 and 5700 Series. The pipeline data of the 3200 and 4200 Series are considered less accurate than those of the 5400, but the flume data of the 3600, 3700, 3800, 3900, 4700 and 4900 Series can be accepted as first-order accuracy.

A series of control runs was carried out to determine the accuracy reported herein. The data themselves are not included, but have been analysed statistically and are reported as such.

B.2 Hydraulic Gradient Determinations:

As has been previously noted, the original manometry system presented many operational difficulties, both in plugging of lead lines and surging of the manometers themselves. The reproducibility of the runs was somewhat improved when pictures were taken of the manometer board for instantaneous readings on all manometers at once. However, the most accurate data are associated with the new manometer system as operated with the modified 2" pipeline.

No separate series of tests was conducted to determine the reproducibility of results as sufficient work was done in the laboratory to convince the author that the final manometry system operated quite satisfactorily and gave consistent reproducible results. To differentiate between the relative accuracy of the pipeline data, it is possible to assign an order of accuracy to the results. The 5400 Series would have to be considered first-order accuracy and as such it provides the best data obtained on slurry characteristics. The 1400 Series on clear water is of the same order of accuracy. Second order of accuracy has been assigned to those data which were obtained with the original manometry system but with photographs taken of the manometry board. The second order of data are those of the 3200 and 4200 Series. The third-order data were those obtained with the original manometry system and read one by one by the operator. The data assigned to this group are included in the 1000, 1100, 1200, 1300, 2000, 2200 and 2300 Series. Within this third group the clear water data are much better than the sand-water slurry data.

It is difficult to assign an absolute accuracy for the data, but the accuracy order should suffice for relative order of accuracy. The data analysis, as shown on the plots of CHAPTER IV, is comparable with the existing literature. The author believes that the data are of at least the same order of accuracy as those published by other workers.

B.3 Determination of Slurry Components:

The slurries used in the testing have been reported as percentages by volume of solids on the total stream, being the conventional way

of reporting such data. The calculation procedures used have been shown in APPENDIX "A" and the analytical techniques are outlined in Section 2.3.

The original technique was to carry out volume and weight determinations in the weigh tank and augment these data by specific gravity determinations using the Denver balance. Theoretically at least, this should work for a two-component mixture such as a sands-water slurry or a fines-water slurry. These were the type of data as reported in Series 2000, 2100, 2200, 2300, 2800 and 2900. Specific gravity determinations were made before and after the weighing period and, if fairly close reproducibility was not achieved, the run was re-done. Only the accepted runs have been reported herein. Although these data have been used in correlation analyses of CHAPTERS IV and V and seem consistent with published data by other workers, they should be considered inferior to data obtained using grab-sample analyses.

The grab-sample procedure was used for all runs in the 3000, 4000 and 5000 Series. In each case, two samples were taken, completely analysed and the percentage concentrations were calculated. A specific gravity was also calculated from the sample analysis. The weigh tank volume and weight data were used to calculate a specific gravity. If the sample analyses were not within 0.5% absolute of each other, the run was discarded. If the specific gravity determinations from the samples and the weigh tank were not within 0.005 of each other, again the run data were discarded. It was felt that this method of data selection and reporting would ensure obtaining quite reliable data interpretation.

Since the concentration determinations involved sampling and analytical laboratory procedures, it seemed reasonable that the results of an extended series of repeat runs should follow a normal distribution. Three series of controlled tests were performed on a fines-water slurry which was transported through the 2" pipeline and returned via the flume on a 2% slope. The first series of tests was carried out at a high discharge rate with no bed condition in the flume. The discharge was then throttled to a point where saltation took place on the bed of the flume and the tests were re-run. Further throttling was conducted until antidunes were formed and a third series of tests was completed. The following sections describe these tests and their statistical evaluation.

B.4 Sample Analyses of a Three-Component Mixture with a Clean Bed in the Flume:

The 7000 Series of tests was carried out on a circulating stream of fines-sand-water slurry. The system was operated with a slurry of approximately 6% fines by volume and 6% sand by volume. Discharge was kept sufficiently high to ensure a clean bed in the flume.

The object of the 7000 Series was not only to test reproducibility of the analyses but also to attempt to detect any surging of solids due to holdup in the system. The timing of the sampling was considered critical in an investigation of possible cyclic effects. The system as adopted can be seen in FIG. B-1, which shows the numerical order of the samples in the squares and the elapsed time as the abscissa. A total of sixty-seven samples was analysed for concentration of solids and specific gravity of the slurry. The mean and standard deviations of each of the values was calculated and can be seen in TABLE B-1.

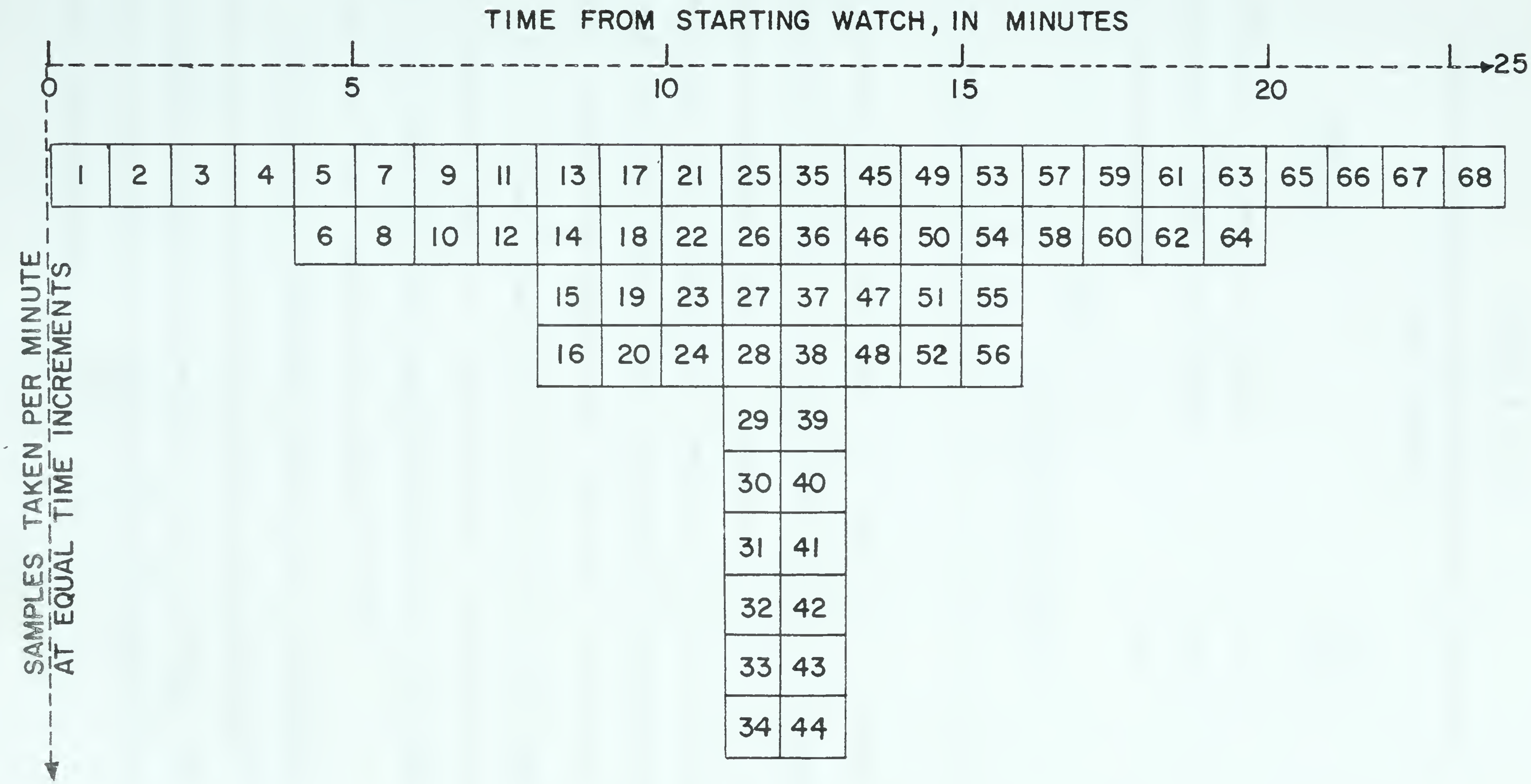

TIME FROM STARTING WATCH, IN MINUTES
0
5
10
15
20
25
SAMPLES TAKEN PER MINUTE
AT EQUAL TIME INCREMENTS
1 2 3 4 5 7 9 11 13 17 21 25 35 45 49 53 57 59 61 63 65 66 67 68
6 8 10 12 14 18 22 26 36 46 50 54 58 60 62 64
15 19 23 27 37 47 51 55
16 20 24 28 38 48 52 56
29 39
30 40
31 41
32 42
33 43
34 44

FIGURE B - I

TABLE B-1

QUALITY CONTROL TESTS ON SAMPLE ANALYSES
(7000 SERIES)

Analysis	Mean	Standard Deviation
Concentration of Fines % by Volume:	6.125	0.194
Concentration of Sand % by Volume:	5.976	0.327
Specific Gravity of Slurry:	1.208	0.006

Note:
a) 67 Samples analysed
b) Clean bed in flume.

The data have been plotted on FIG. B-2, which shows the values plotted against time of sampling. The standard deviations and the graphs illustrate the good reproducibility of sample analyses. The fines component can be thought of as suspended in a continuous fluid phase and the three major discrepancies shown on FIG. B-2 could be considered discrepancies due to analytical technique rather than actual variation in the slurry.

The variations in the sand concentrations are most likely due to minor holdup in the system. FIG. B-2 shows no well-defined cyclic effect. The variations in the specific gravity shown on the plots reflect the variations in sand concentration rather than fines.

The 7000 Series establishes that the data of the 5400 and 5700 Series are quite good with respect to slurry component determination. The possibility of major holdup such as a bed in the flume could cause difficulty in light of FIG. B-2 and as such a new series of tests was carried out to determine such an effect.

ACCURACY OF SOLIDS CONCENTRATION FOR
CLEAN BED TESTS.

DATA TAKEN FROM SERIES 7000

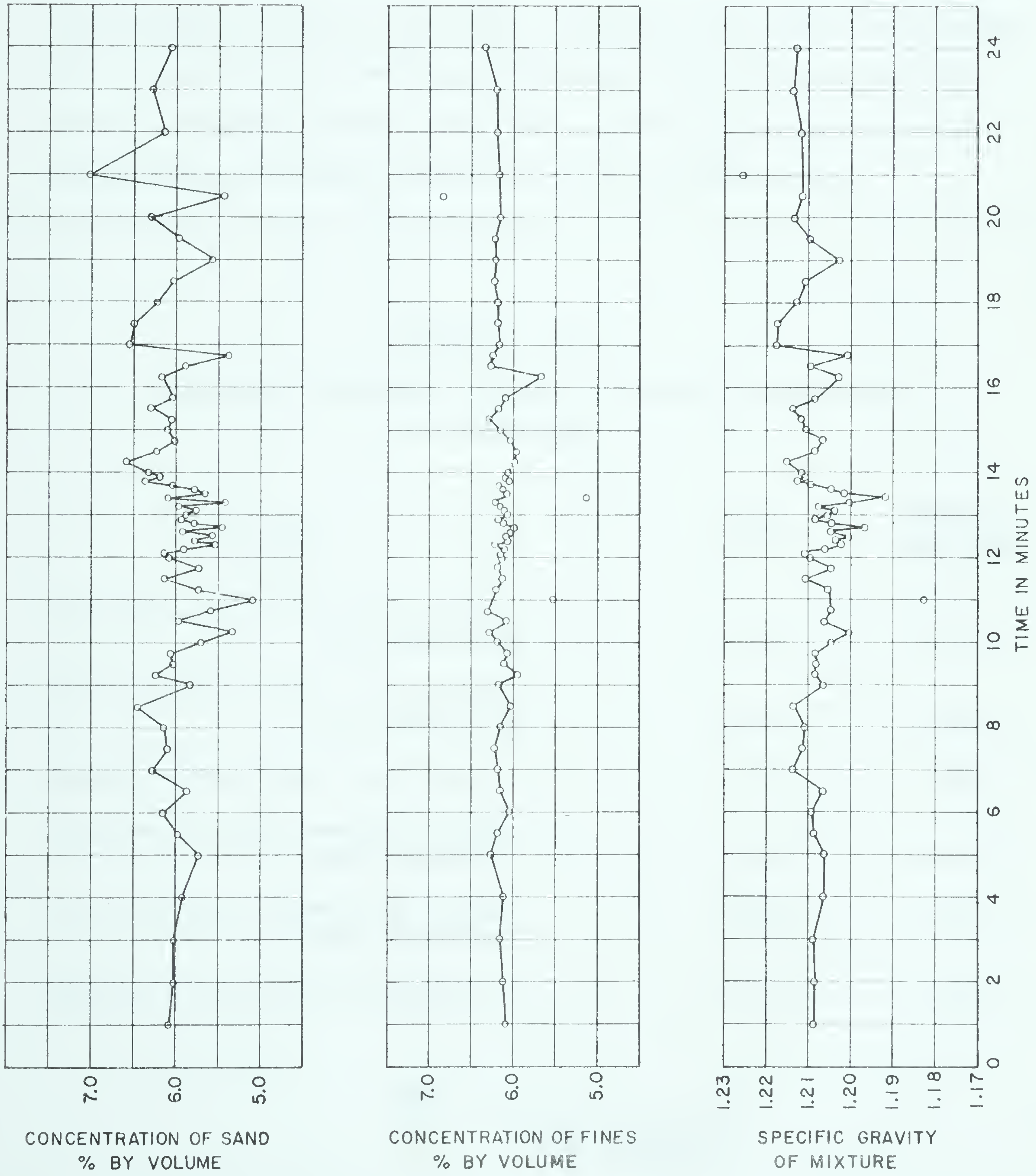


FIGURE B-2

B.5 Accuracy of Component Determinations for Critical Deposit Conditions:

The 7100 Series was carried out in the same manner shown in FIG. B-1, immediately after completion of the 7000 Series, so that the circulating stream was essentially the same. The discharge was throttled sufficiently so that a saltating bed could be determined through the plexiglass section of the flume. It should be noted that no continuous bed was present, only saltating sand grains on the bottom of the flume. Of the sixty-eight samples, fifty were analysed and eighteen were discarded because of either sampling error or analytical error.

TABLE B-2

QUALITY CONTROL TESTS ON SAMPLE ANALYSES (7100 SERIES)

Analysis	Mean	Standard Deviation
Concentration of Fines % by Volume over whole run:	6.510	0.113
Concentration of Sand % by Volume over whole run:	5.350	0.583
Specific Gravity over whole run:	1.200	0.009
Concentration of Fines % by Volume after 8 minutes:	6.520	0.113
Concentration of Sand % by Volume after 8 minutes:	5.180	0.295
Specific Gravity after 8 minutes:	1.197	0.004

Note:
50 Sample analyses - sand saltating.

ACCURACY OF SOLIDS CONCENTRATION FOR
INCIPIENT ANTIDUNE FORMATION CONDITIONS.

DATA TAKEN FROM SERIES 7100

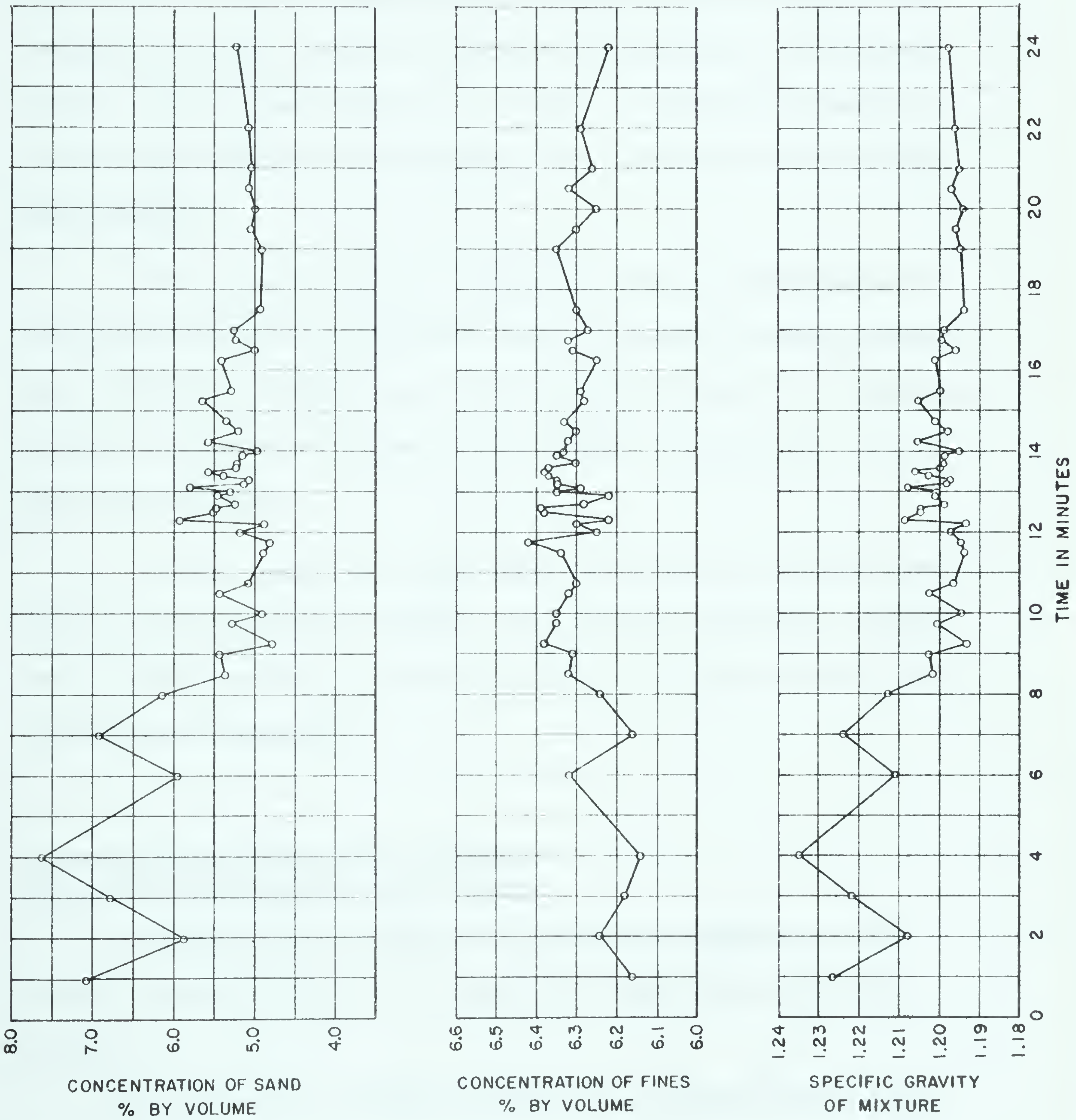


FIGURE B-3

The data are reported in TABLE B-2 and have been plotted in FIG. B-3. The first eight minutes of the sampling period were characterised by very high sand concentrations with relatively low fines concentrations. This effect was caused by irregular deposition in the headbox of the flume, ponding and resulting discharge surges to the weigh tank. Once a uniform saltating bed had formed, the samples showed a fairly steady analysis. The data of TABLE B-2 indicate that the analyses were considerably more uniform after these initial eight minutes.

The 7100 Series shows a slight increase in concentration of fines from that of the 7000 Series, with a decrease in sand concentration. Both these changes are consistent with the hold-up of some sand while it is saltating on the bed. The specific gravity of the slurry reflects these changes.

The flow regime for these tests was that of the incipient antidune or critical deposit condition. The antidune formation, partial bed or jerking bed were much more difficult to analyse from a solids concentration standpoint.

B.6 Component Determinations of Slurries with a Bed Formation in the Flume:

The 7200 Series of sixty-eight tests was performed in the manner outlined in FIG. B-1. Seven tests were discarded in this series.

The data are reported in TABLE B-3 and have been plotted in FIG. B-4. The effect of the antidunes is very pronounced, showing a great fluctuation of concentrations of solids. The cyclic effect

ACCURACY OF SOLIDS CONCENTRATION FOR BED CONDITION IN THE FLUME.

DATA TAKEN FROM SERIES 7200

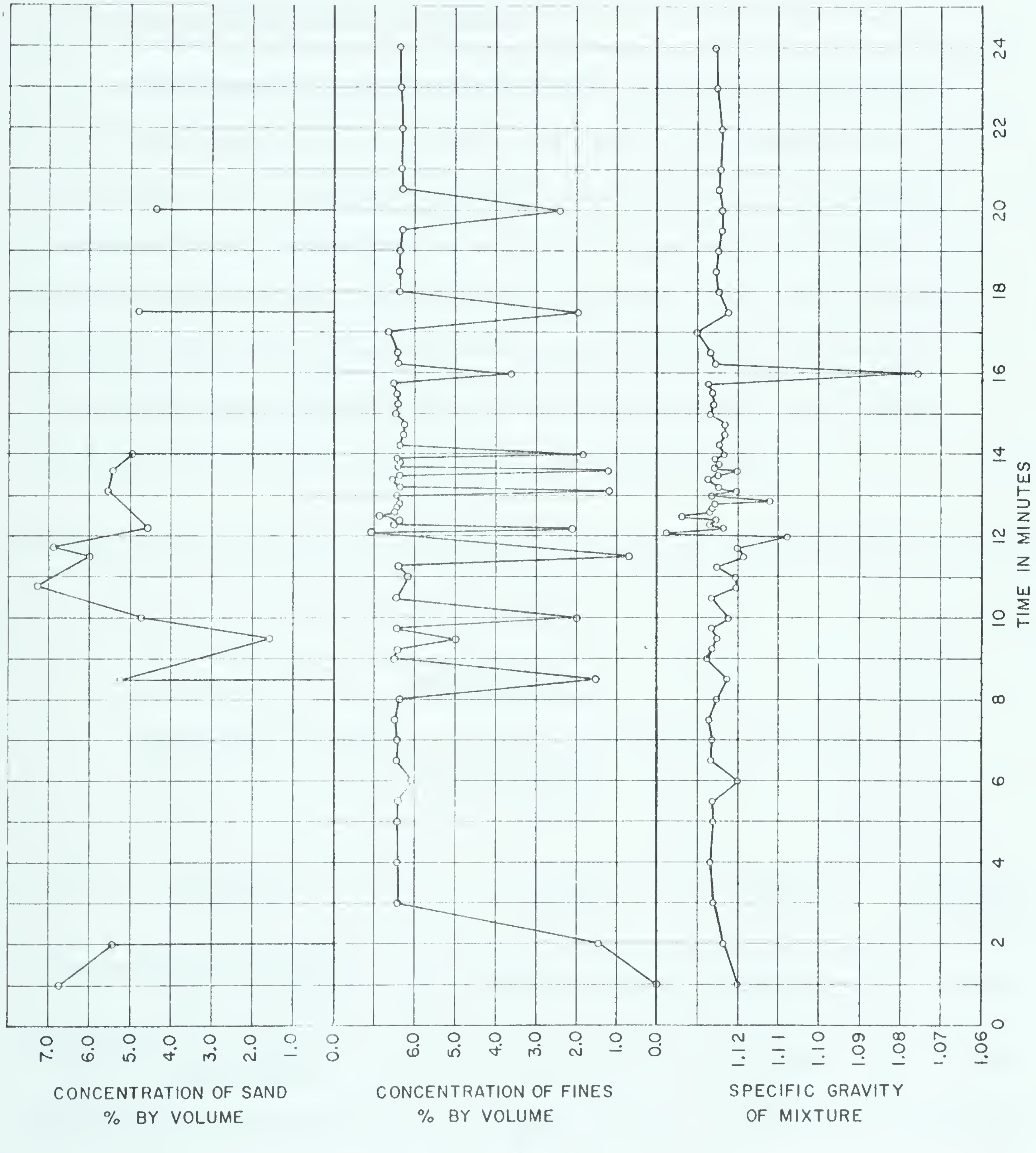


FIGURE B-4

of large sand concentrations was caused by the antidune reaching the headbox, being dissipated with the sand going into suspension and moving down the flume until another antidune formed near the diversion section of the flume. The partial and jerking bed conditions reflected these same cyclic variations.

This series of tests indicates that no accurate determination of the sand concentrations could be made while the antidunes were in the system. This presented no great difficulty, since it was possible to determine the concentrations of fines and sand before the discharge was throttled to a point where antidunes formed. This in fact was the procedure followed and all concentrations shown in the 5700 Series were of this type. The procedures followed in the 2800 and 2900 Series were also carried out before the antidunes formed.

TABLE B-3

QUALITY CONTROL TESTS ON SAMPLE ANALYSES
(7200 SERIES)

Analysis	Range	Mean	Standard Deviation
Concentration of Fines % by Volume:	0.00 - 9.05	5.890	2.163
Concentration of Sand % by Volume:	0.00 - 7.21	0.940	2.048
Specific Gravity of Slurry:	1.066 - 1.155	1.116	0.010

B.7 Accuracy of Discharge Measurements:

The discharge determination technique has been outlined in Section 2.3. As has been noted, monthly inspections of the scale were made by the manufacturer and regular checks were made comparing the volume and weight measurements for clear water.

During the actual runs, the discharge was quickly calculated from the volume-time relationship and was compared for order of magnitude against a chart which showed head loss vs. discharge for the 2" pipeline. If there was a wide discrepancy the run was re-done.

The 7300 Series was carried out to determine accuracy of discharge data over a range of flow rates. The data for these tests are shown in TABLE B-4.

TABLE B-4

DISCHARGE ACCURACY DATA

(7300 SERIES)

Flow Rate	N° of Tests	Mean $Ft.^3/Sec.$	Standard Deviation
High Rate	11	0.2115	0.0042
Rate #2	11	0.1787	0.0046
Rate #3	10	0.1252	0.0031
Low Rate	10	0.0856	0.0047

All tests in the 7300 Series were made using the sump tank drawdown to provide the weigh water, rather than try makeup to this system from the reservoir tank. Since the characteristic curve of the pump was quite flat, as shown in FIG. II-3, a series of tests was carried out to evaluate the effect of sump drawdown.

B.8 Accuracy of Discharge Data with Sump Drawdown Effects:

The 7400 and 7500 Series were carried out to evaluate the effect of sump tank drawdown on the discharge measurements. During a weigh, the sump tank was allowed to draw down to a maximum of approximately one foot. This meant that during the weighing period the average positive suction head could be reduced by one-half foot of liquid, or approximately 0.25 psig. The pump curve shown on FIG. II-3 indicates that a decrease in head of 0.25 psig corresponds to a decrease in discharge of 0.015 cfs. This possible decrease was considered minor for high discharge rates, but a series of tests was made to determine the actual effect of sump tank drawdown.

The 7400 Series consisted of eighty tests using clear water through the 2" pipeline and the flume laid on a 2% slope. The first forty tests were made at a constant discharge. During tests 7400 to 7425 inclusive, the sump tank was drawn down. The sump tank level was maintained at a constant level for tests 7426 to 7440. The results of these tests can be seen in TABLE B-5. Results are anomalous, since the mean discharge was 0.015 cfs higher for sump tank drawdown than for constant level.

A second discharge rate was tested for runs 7443 to 7480, with 7443 to 7467 inclusive maintaining constant level and 7468 to 7480 utilizing sump tank drawdown. These tests show a difference in mean discharge of 0.003 cfs, with the steady-level discharge being slightly higher, as expected.

TABLE B-5

SUMP TANK DRAWDOWN TESTS, CLEAR WATER (7400 SERIES)

Series (Inclusive)	Type of Test	Mean Discharge cfs.	Standard Deviation cfs.
7400 - 7435	Drawdown	0.2554	0.0070
7426 - 7440	Steady-Level	0.2403	0.0088
7400 - 7440		0.2523	0.0088
7443 - 7467	Steady-Level	0.2157	0.0060
7468 - 7480	Drawdown	0.2124	0.0086
7443 - 7480		0.2146	0.0072

Note:
a) Tests 7400 to 7440 inclusive at constant discharge rate #1;
b) Tests 7443 to 7480 inclusive at constant discharge rate #2.

The 7500 Series was carried out with a fines-sand-water slurry, discharging through the 2" pipeline and returning via the 2" return line. The first twenty tests were made utilizing sump tank drawdown, while the final twenty were carried out with steady-level operation. The results shown in TABLE B-6 again illustrate a slightly higher mean discharge rate for the steady-level operation.

TABLE B-6

SUMP TANK DRAWDOWN TESTS, FINES-SAND-WATER SLURRY (7500 SERIES)

Series (Inclusive)	Type of Test	Mean Discharge cfs.	Standard Deviation cfs.
7500 - 7520	Drawdown	0.2119	0.0211
7521 - 7540	Steady-level	0.2165	0.0087

Note: All tests at constant discharge rate.

At high solids concentrations, the reservoir tank was difficult to operate without settling of solids in the corners of the tank. This resulted in non-uniform makeup from the reservoir tank to the sump tank during the weigh. Since the data presented in TABLES B-5 and B-6 indicate that there was no significant difference between the discharges obtained for either sump drawdown or constant level, it was decided to use the sump tank drawdown procedure in all runs and this was practised in all the series except for the 2000, 2100, 2200, 2300, 2800 and 2900 Series.

B.9 Accuracy of Flume Depth Measurements:

The flume gauge section, which is shown on PLATE 2-11, consisted of two needle-point probes, spaced 20 feet apart, in the flume. Each gauge was set so that the needle just touched the surface of the fluid; the readings were taken and the mean depth was calculated. If the mean depth was significantly different from either of the individual gauge readings, the data for that run were excluded.

It has been noted that, as the fines concentration of the fluid increased, noticeable waves were present in the flume. These waves were rather difficult to allow for when setting the depth gauge. A series of tests was carried out to determine the reproducibility of the mean depths. The procedure followed was for one operator to set the depths and another to take the readings on the micrometer gauges and then to raise the needle point off the water surface for the first operator to re-set. Results of these runs are shown in TABLE B-7. The depths were read in conjunction with the sump tank drawdown tests of the 7300 and 7400 Series.

TABLE B-7

ACCURACY OF FLUME DEPTH MEASUREMENTS

Series	N° of Tests	Mean Depth	Standard Deviation
7400 - 7440	40	0.1096	0.0090
7443 - 7480	38	0.0933	0.0009
7304 - 7314	11	0.0939	0.0006
7336 - 7345	10	0.0517	0.0013

As can be seen in these tests, the runs were carried out only on clear water. Some runs were performed on the slurries, but unfortunately the data were either misplaced or lost and therefore cannot be reproduced herein. There can be no doubt that operator experience was quite a vital factor. The procedure was to immerse the needle point to a depth that corresponded to the mid-point of the amplitude of the waves. However, the reproducibility of the depths was quite remarkable in light of the waves on the surface of the flume.

In light of the testing carried out, it was concluded that the needle-point gauges were adequate instrumentation and that the accuracy of measurements was quite acceptable.

APPENDIX "C"

APPENDIX "C"

RHEOLOGICAL INVESTIGATIONS

C.1 General:

A separate rheological investigation was carried out on slurries of both sludge and fines-water mixture. As previously discussed, these slurries were considered a homogeneous, continuous fluid phase for all one- and two-component mixtures. It is generally accepted that such slurries in significant concentrations with solids exhibit non-Newtonian behaviour. The object of the rheological investigations was to derive a measure of the consistency of these slurries which could be used as a comparable parameter to viscosity in the case of Newtonian fluids.

The 31,000 Series was carried out on samples of sludge taken from the slurries tested in the pipeline and flume during the 3000 Series. The 41,000 Series of tests was conducted on prepared slurries of fines and water. The fines were taken from representative samples of the solids used in the 4000 Series for pipeline and flume testing. These slurries were prepared in small batches over a range of concentrations of solids. The 42,000 Series was made on samples taken from the actual slurries used during the 4000 Series testing.

The approach employed was to follow the technique outlined by Govier (1960). A concentric-cylinder rotational viscometer Model 35, manufactured by the Fann Instrument Corporation, was used for all the testing. This viscometer operates on the principle that a torque

can be transmitted from a rotor to a stator by the fluid filling the annulus between the cylinders. In the case of the Model 35, the outer cylinder is rotated and the torque is measured on the inner cylinder. The two measured variables are: revolutions per minute of the outer cylinder and deflections in degrees of a torsion balance on the inner cylinder. The viscometer can be calibrated using known Newtonian fluids.

C.2 Calibration of the Viscometer:

The viscometer was calibrated using Newtonian fluids of water and water-glycerol with known viscosities. The laminar viscosity for these Newtonian fluids is defined by the relation -

$$\mu = \frac{\tau}{\frac{du}{dr}} \quad \ldots \ldots \ldots \ldots \ldots \quad (C-1)$$

where -

μ = Absolute viscosity in lbs. sec./ft.^{2}

τ = Shear stress in lbs./ft.^{2}

$\frac{du}{dr}$ = Velocity gradient in sec.$^{-1}$

The instrument-measured variables are -

N = Revolutions per second of the rotor

θ = Deflection of torque-measuring device in degrees.

The rate of shear or velocity gradient for Newtonian fluids at the stator is defined by the relation -

$$\left(\frac{du}{dr}\right)_i = \frac{4\pi}{1-\frac{1}{s^2}} N \quad \ldots \ldots \ldots \ldots \ldots \quad (C-2)$$

where - s = ratio of the rotor diameter to the stator diameter.

Since the expression $\frac{4\pi}{1-\frac{1}{s^2}}$ is a function of the viscometer geometry, (C-2) can be written as -

$$\left(\frac{du}{dr}\right)_i = K_1 N \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (C-3)$$

where -

$$K_1 = \frac{4\pi}{1-\frac{1}{s^2}}$$

The shear stress at the stator wall is directly proportional to the measured deflection of the torsion balance.

$$\tau_i = K_2 \theta \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (C-4)$$

where -

τ_i = Shear stress at the stator wall in lbs./ft.^{2}

K_2 = Constant of proportionality in $\frac{\text{lbs.}}{\text{ft.}^2 \times \text{degrees of deflection}}$

The velocity gradient at the stator wall can be expressed for Newtonian fluids as -

$$\left(\frac{du}{dr}\right)_i = \frac{\tau_i}{\mu} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (C-5)$$

by combining (C-4) and (C-5) -

$$\left(\frac{du}{dr}\right)_i = \frac{K_2 \theta}{\mu} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (C-6)$$

and using (C-3) -

$$K_2 = \frac{\mu}{\theta} N K_1 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (C-7)$$

Two different rotors were used during the viscometer investigation. These were identified as Rotors 1 and 2. For Rotor 1, $K_{11} = 505.28287$ and for Rotor 2, $K_{12} = 102.55741$.

The value of K_2 was found to be slightly variable during repeat runs for both rotors, but after considerable testing and study the constant was accepted - $K_2 = 2.19 \times 10^{-3}$ for both rotors.

C.3 Use of Viscometer with Non-Newtonian Fluids:

Both Govier (1962) and Lindley (1958) have discussed the use of the rotational viscometer with non-Newtonian fluids. They have used the following expression to calculate the velocity gradient at the stator wall -

$$\left(\frac{du}{dr}\right)_i = K_1 N \left[1 + K_3 \left(\frac{1}{n^{11}} - 1\right) + K_4 \left(\frac{1}{n^{11}} - 1\right)^2\right] \quad \ldots\ldots \quad \text{(C-8)}$$

where -

$$K_3 = \frac{s^2 - 1}{2 s^2} \left(1 + \frac{2}{3} \ln s\right)$$

$$K_4 = \left(\frac{s^2 - 1}{6 s^2}\right) \ln s$$

n^{11} is the slope of a log-log plot of θ vs. N.

For Rotor 1 -

$$K_{31} = 1.2537 \times 10^{-2}$$
$$K_{41} = 5.21352 \times 10^{-5}$$

For Rotor 2 -

$$K_{32} = 6.393 \times 10^{-2}$$
$$K_{42} = 1.33 \times 10^{-3}$$

C.4 Data Recording:

The data as collected during the viscometer measurements were recorded on sheets as shown on TABLE C-1. All of the original data are available on file at the University of Alberta, but only the processed data are included in APPENDIX "F".

TABLE C-1

DATA SHEET FOR RHEOLOGICAL INVESTIGATION

1.	Run Number	-	41018
2.	Date	-	091361
3.	Type of Fluid	-	Synthetic Fines-Water
4.	Temperature	-	25.0° C.
5.	Solids Concentration	-	23.63 Wt. %
6.	Total Weight + Tare	-	200.93 gms.
7.	Dry Weight + Tare	-	86.28 gms.
8.	Tare	-	50.93 gms.
9.	Rotor Number	-	2
10.	Deflection, at -		

600	RPM	-	55.15 deg.
300	"	-	37.15 "
200	"	-	30.55 "
100	"	-	22.48 "
6	"	-	11.55 "
3	"	-	10.85 "

C.5 Data Processing:

As discussed in CHAPTER III, both the sludge and the fines-water slurry were considered most closely approximated by the Bingham Plastic model.

The original data were punched on cards and processed on the IBM 1620 computer at the University of Alberta. The procedure used was as follows :

Let $\text{Log } N = x$ . . . . (C-9)

$\text{Log } \theta = y$ . . . . (C-10)

These transformed variables were used in the linear regression technique discussed in APPENDIX D.5. The correlation coefficient was calculated in the manner shown in APPENDIX D.6.

Since the plot of Log θ vs. Log N was considered linear at high rates of shear, only values of $N \geq 100 \text{ sec}^{-1}$ were used. This meant that the best fit line was calculated for four points.

In the event that the correlation coefficient was $\lessgtr 0.90$, the program was designed to discard the lowest speed and carry out the regression on the remaining three points. The lowest correlation coefficient calculated was 0.968, but the bulk were $0.980 \leq r^2 \leq 1.00$, indicating an excellent linear relationship between the transformed x and y.

Following the argument of Govier (1962), the slope of $y = ax + b$ was recorded as $n^{11} = a$ . . . . (C-11)

A sample plot for Run N° 41018 can be seen on FIG. III-4. The value n^{11} as taken from this plot is 0.50 and the same value as

calculated on the computer is 0.49997. The values of n^{11} for the rheological data are not included in the data of APPENDIX "F".

The values of θ were converted to shear stress using equation (C-4). The values of N were converted to velocity gradients using equation (C-3).

The hypothesis of a Bingham Plastic model, as discussed in CHAPTER III, predicts a linear relationship between the shear stress and the velocity gradient of the form $\tau = \eta\left(\frac{du}{dr}\right) + \tau_y$ . . . . (C-12)

where -

η = Coefficient of rigidity in lbs. sec./ft.^{2}

τ_y = Yield stress in lbs./ft.^{2}

A regression analysis of τ on $\frac{du}{dr}$ was carried out on the computer, using the method outlined in APPENDIX D.4. If the correlation coefficient for the regression line was $\bar{<}0.90$ (as defined in APPENDIX D.6), the regression was re-done after excluding the lowest value of N and corresponding θ. This was repeated until the correlation coefficient was >0.90.

The coefficient of rigidity was divided by the mass density of the fluid, to obtain the apparent kinematic viscosity -

$$\nu_a = \frac{\eta}{\rho} \quad \ldots\ldots\ldots\ldots\ldots \quad \text{(C-13)}$$

where -

ν_a = Apparent kinematic viscosity in ft.^{2}/sec.

ρ = Mass density in slugs/ft.^{3}

The data presented herein can be found in TABLES F-24, F-25 and F-26. The following data are included:

Run Number: Serial number of test.

Date: Date of viscometer work.

Temperature, °F.: Temperature of slurry in rotor cup.

Concentration of Solids in by Volume.

Coefficient of Rigidity in $\frac{\text{lbs./sec.}}{\text{ft.}^2}$

Apparent Yield Stress in $\frac{\text{lbs.}}{\text{ft.}^2}$

Specific Gravity of Slurry.

Apparent Kinematic Viscosity in $\frac{\text{ft.}^2}{\text{sec.}}$

APPENDIX "D"

APPENDIX "D"

DATA PROCESSING

D.1 General:

A great deal of data processing was carried out using the IBM 1620 computer at the University of Alberta. In the case of the processed data of APPENDIX "F", the calculations are straightforward and have been shown in APPENDIX "A". However, there are instances when linear regression techniques and statistical parameters have been used. This Appendix is included to show specifically the calculation procedures for these cases.

D.2 Arithmetic Mean:

The arithmetic mean is reported herein for the quality control data of APPENDIX "B" and flume depths. For a series of N values of x_i, (i = 1 to N) the mean is given by the relation -

$$\text{Arithmetic Mean} = \bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i \quad \ldots\ldots\ldots\ldots \quad \text{(D-1)}$$

D.3 Standard Deviation:

The standard deviation is used in APPENDIX "B" as a measure of the dispersion about the arithmetic mean. It is given by the relation -

$$\text{Standard Deviation} = \sigma = \left[\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2 \right]^{\frac{1}{2}} \quad \ldots\ldots\ldots \quad \text{(D-2)}$$

D.4 Linear Regression:

During the analysis of the data, several plots were made on arithmetic coordinates. Choosing y as ordinate and x as abscissa, the regression line of y on x was obtained as follows:

Find the best fit straight line for x and y, using the method of least squares:

$$\text{Let } Y = ax + b \quad \text{(D-3)}$$

The error e_i for any point as measured y_i and predicted Y_i is -

$$e_i = y_i - Y_i = y_i - ax_i - b \quad \text{(D-4)}$$

The best fit line will result when -

$$\sum_{i=1}^{n} (e_i)^2 = E = \text{minimum value} \quad \text{(D-5)}$$

that is,

$$\frac{\partial E}{\partial a} = 0 = -2 \sum_{i=1}^{n} (x_i)(y_i - ax_i - b) \quad \text{(D-6)}$$

$$\frac{\partial E}{\partial b} = 0 = -2 \sum_{i=1}^{n} (y_i - ax_i - b) \quad \text{(D-7)}$$

Equations (D-6) and (D-7) can be solved simultaneously for a and b, giving -

$$b = \frac{\sum_{i=1}^{n} (y_i) - a \sum_{i=1}^{n} (x_i)}{n} \quad \text{(D-8)}$$

$$a = \frac{n \sum_{i=1}^{n} (x_i\, y_i) - \left(\sum_{i=1}^{n} (x_i)\right)\left(\sum_{i=1}^{n} (y_i)\right)}{n \sum_{i=1}^{n} (x_i)^2 - \left(\sum_{i=1}^{n} (x_i)\right)^2} \quad \text{(D-9)}$$

The regression line of y on x is therefore defined as -

$$\underline{y} = ax + b \quad \text{(D-10)}$$

D.5 Linear Regression of Transformed Variables:

Some of the data, when plotted on log-log coordinates, showed a good straight line fit. Choosing Log Y as the ordinate and Log X as the abscissa, the linear regression of log Y on log X was obtained as follows:

$$\text{Let Log } Y = y \quad \ldots\ldots\ldots\ldots \quad \text{(D-11)}$$

$$\text{Log } X = x \quad \ldots\ldots\ldots\ldots \quad \text{(D-12)}$$

$$\text{Log } C = b$$

A linear regression of y on x can be carried out as shown in Section D. 4, giving -

$$y = ax + b \quad \ldots\ldots\ldots\ldots \quad \text{(D-10)}$$

Transferring back -

$$\text{Log } Y = a \log X + \log C \quad \ldots\ldots\ldots\ldots \quad \text{(D-13)}$$

Taking anti-logs -

$$Y = CX^a \quad \ldots\ldots\ldots\ldots \quad \text{(D-14)}$$

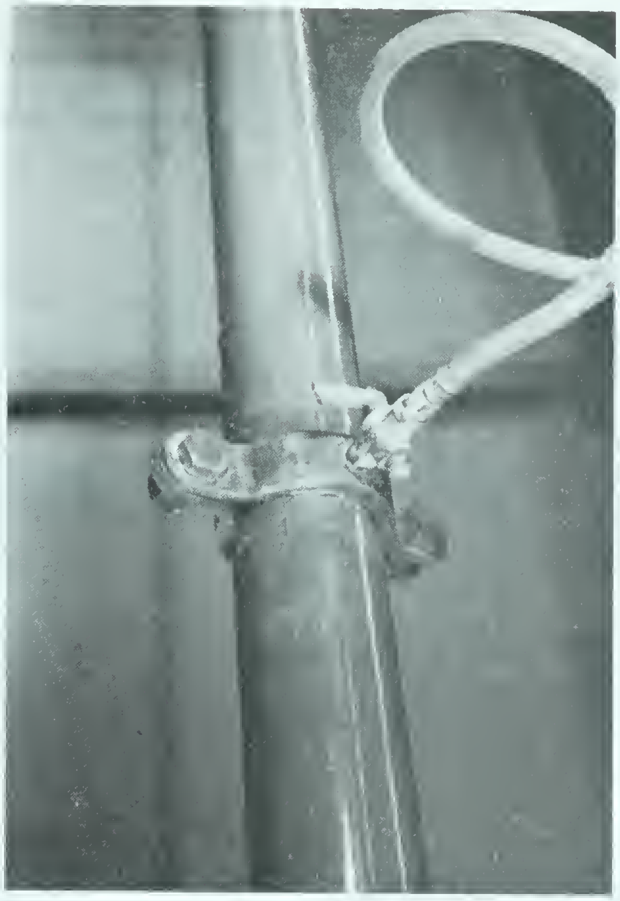
D.6 Correlation Coefficient:

The correlation coefficient for the y on x linear regression is defined as:

$$r^2 = \frac{\left[n \sum_{i=1}^{n} x_i y_i - \left(\sum_{i=1}^{n} (x_i) \right) \left(\sum_{i=1}^{n} (y_i) \right) \right]^2}{\left[n \sum_{i=1}^{n} (x_i)^2 - \left(\sum_{i=1}^{n} (x_i) \right)^2 \right] \left[n \sum_{i=1}^{n} (y_i)^2 - \left(\sum_{i=1}^{n} (y_i) \right)^2 \right]} \quad \ldots\ldots \quad \text{(D-16)}$$

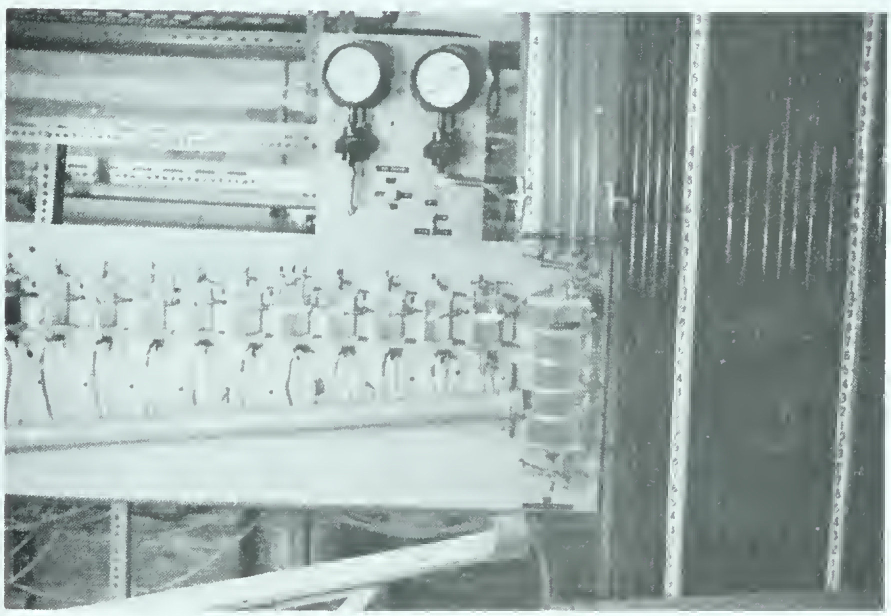
It is customary to report the coefficient as r rather than r^2. However, the IBM program was available for the r^2 coefficient and so was used herein.

APPENDIX "E"

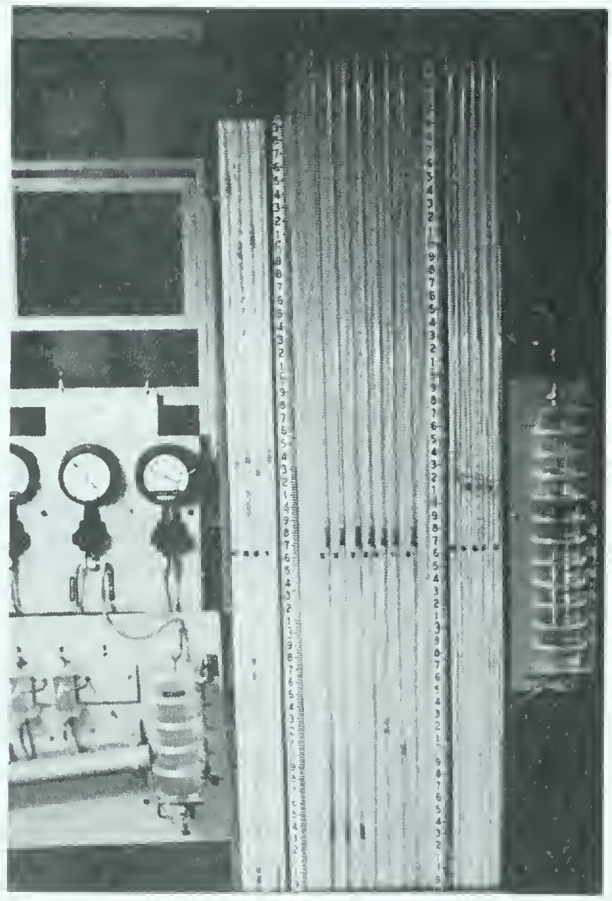


2" PIEZOMETER TAP

VIEW OF TEST PIPING & FLUME



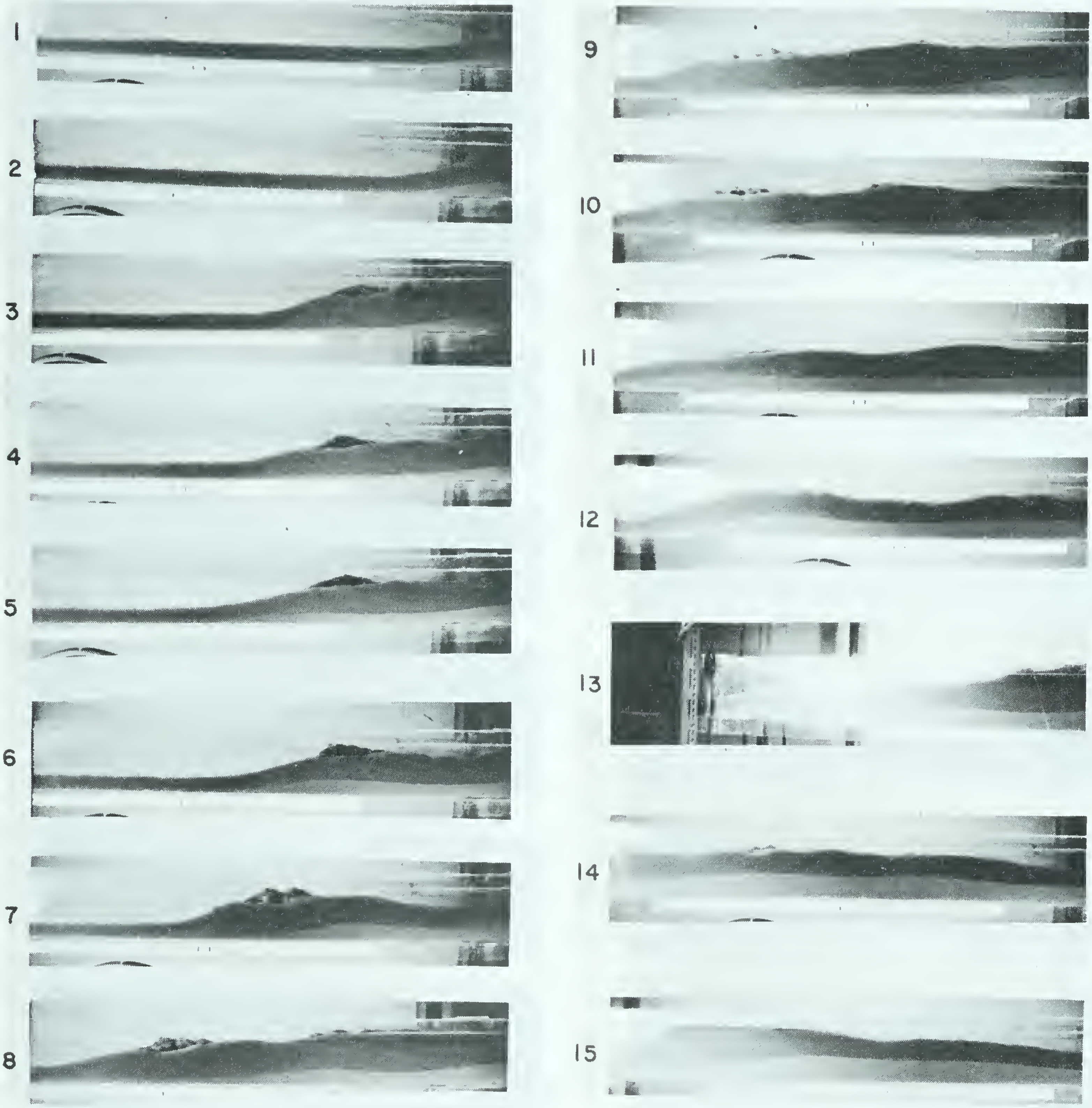
MANOMETER SEDIMENT POTS



MANOMETER BOARD

MISCELLANEOUS TEST EQUIPMENT

PLATE E-1



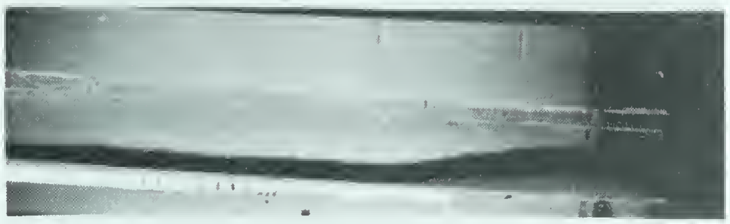
SEQUENCE OF 15 PHOTO'S SHOWING ANTIDUNE BEHAVIOUR — — PHOTO SERIES I — — PHOTOGRAPHED AT APPR. 5 SECOND INTERVALS

DISCHARGE = 0.312 FT.^{3}/SEC. FLUME SLOPE = 2% CONCENTRATION OF SAND = 2% BY VOLUME

PLATE E – 2

1

2



3

4

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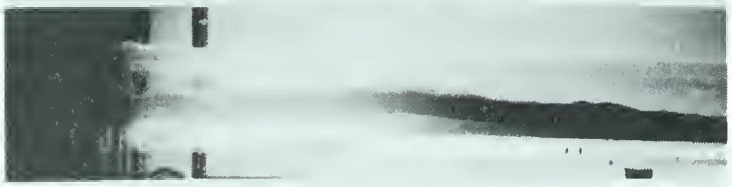
11



12

13

14

15

16

17

18

SEQUENCE OF 18 PHOTO'S SHOWING ANTIDUNE BEHAVIOUR — PHOTO SERIES 2 -- PHOTOGRAPHED AT 5 SECOND INTERVALS

- DISCHARGE = 0.206 $FT.^3/SEC.$ -- FLUME SLOPE = 2%
- CONCENTRATION OF SAND 2% BY VOLUME

PLATE E-3

APPENDIX "F"

TABLE F-1

1000 SERIES - CLEAR WATER, 1" STEEL PIPE

Run Nº	Date	Kinematic Viscosity $Ft^2/Sec.$	Discharge, $Ft^3/Sec.$	Velocity, Ft./Sec.	Hydraulic Gradient, Ft. of H_2O/Ft	Reynolds Number	Friction Factor
1001	7/27/60	.0000098	.079	13.174	1.530	117494.8	.0496
1002	7/27/60	.0000095	.079	13.089	1.520	120423.1	.0499
1003	7/27/60	.0000091	.073	12.088	1.330	116095.2	.0512
1004	7/27/60	.0000089	.062	10.289	.970	101042.5	.0515
1005	7/27/60	.0000089	.042	7.002	.480	68763.9	.0550
1006	7/27/60	.0000088	.008	1.398	.020	13889.2	.0575
1026	6/12/61	.0000098	.045	7.446	.820	66403.0	.0832
1027	6/12/61	.0000098	.045	7.577	.840	67577.3	.0823
1028	6/12/61	.0000098	.044	7.349	.770	65540.8	.0802
1029	6/12/61	.0000098	.043	7.169	.750	63935.4	.0821
1030	6/12/61	.0000095	.034	5.720	.600	52628.5	.1031
1031	6/12/61	.0000095	.034	5.732	.450	52735.9	.0770
1032	6/12/61	.0000095	.029	4.849	.400	44608.5	.0957
1033	6/12/61	.0000092	.026	4.310	.260	40948.5	.0787
1034	6/12/61	.0000092	.020	3.405	.130	32350.3	.0630
1035	6/12/61	.0000092	.013	2.102	.030	19967.6	.0382
1051	7/10/61	.0000095	.028	4.650	.258	42783.7	.0671
1052	7/10/61	.0000095	.025	4.117	.283	37876.6	.0939
1053	7/10/61	.0000088	.025	4.084	.258	40558.4	.0870
1054	7/10/61	.0000088	.024	3.984	.261	39565.2	.0925
1055	7/10/61	.0000088	.024	3.950	.246	39234.1	.0886
1056	7/10/61	.0000088	.022	3.684	.215	36585.4	.0891
1057	7/10/61	.0000086	.021	3.450	.200	35064.7	.0945
1058	7/10/61	.0000086	.013	2.084	.073	21174.3	.0946
1059	7/10/61	.0000086	.017	2.834	.154	28797.1	.1079
1060	7/10/61	.0000086	.019	3.167	.169	32184.9	.0948

TABLE F-2

1100 SERIES - CLEAR WATER, 1" ALUMINUM PIPE

Run Nº	Date	Kinematic Viscosity $Ft^2/Sec.$	Discharge, $Ft^3/Sec.$	Velocity, Ft./Sec.	Hydraulic Gradient Ft. of H_2O/Ft	Reynolds Number	Friction Factor
1101	7/27/60	.0000098	.079	13.174	1.550	117494.8	.0502
1102	7/27/60	.0000095	.079	13.089	1.540	120423.1	.0505
1103	7/27/60	.0000091	.073	12.088	1.320	116095.2	.0508
1104	7/27/60	.0000089	.062	10.289	.990	101042.5	.0526
1105	7/27/60	.0000089	.042	7.002	.500	68763.9	.0573
1106	7/27/60	.0000088	.008	1.398	.040	13889.2	.1150
1125	6/12/61	.0000098	.046	7.649	.216	68216.5	.0208
1126	6/12/61	.0000098	.045	7.446	.198	66403.0	.0201
1127	6/12/61	.0000098	.045	7.577	.201	67577.3	.0197
1128	6/12/61	.0000098	.044	7.349	.191	65540.8	.0199
1129	6/12/61	.0000098	.043	7.169	.186	63935.4	.0204
1130	6/12/61	.0000095	.034	5.720	.149	52628.5	.0256
1131	6/12/61	.0000095	.034	5.732	.124	52735.9	.0212
1132	6/12/61	.0000095	.029	4.849	.095	44608.5	.0227
1133	6/12/61	.0000092	.026	4.310	.079	40948.5	.0239
1134	6/12/61	.0000092	.020	3.405	.052	32350.3	.0252
1135	6/12/61	.0000092	.013	2.102	.025	19967.6	.0318
1151	7/10/61	.0000095	.028	4.650	.079	42783.7	.0205
1152	7/10/61	.0000095	.025	4.117	.063	37876.6	.0209
1153	7/10/61	.0000088	.025	4.084	.067	40558.4	.0226
1154	7/10/61	.0000088	.024	3.984	.061	39565.2	.0216
1155	7/10/61	.0000088	.024	3.950	.058	39234.1	.0209
1156	7/10/61	.0000088	.022	3.684	.056	36585.4	.0232
1157	7/10/61	.0000086	.021	3.450	.046	35064.7	.0217
1158	7/10/61	.0000086	.013	2.084	.022	21174.3	.0285
1159	7/10/61	.0000086	.017	2.834	.037	28797.1	.0259
1160	7/10/61	.0000086	.019	3.167	.043	32184.9	.0241

TABLE F-3

1200 SERIES - CLEAR WATER, INITIAL 2" STEEL PIPE

Run Nº	Date	Kinematic Viscosity Ft.^{2}/Sec.	Discharge, Ft^3/Sec.	Velocity, Ft./Sec.	Hydraulic Gradient, Ft.of H_2O/Ft.	Reynolds Number	Friction Factor
1201	6/23/60	.0000099	.289	12.511	.228	216724.3	.0161
1202	6/23/60	.0000095	.036	1.558	.004	28133.5	.0182
1203	6/24/60	.0000090	.141	6.104	.064	116311.2	.0190
1204	6/24/60	.0000093	.099	4.286	.031	79031.0	.0186
1205	6/24/60	.0000093	.052	2.251	.012	41511.2	.0261
1226	7/28/60	.0000092	.303	13.117	.246	244511.8	.0158
1227	7/28/60	.0000090	.276	11.948	.205	227673.0	.0158
1228	7/28/60	.0000090	.243	10.519	.159	200451.2	.0159
1229	7/28/60	.0000088	.154	6.667	.068	129922.1	.0169
1230	7/28/60	.0000088	.116	5.022	.040	97863.4	.0175
1231	7/29/60	.0000090	.088	3.809	.026	72591.4	.0198
1232	7/29/60	.0000088	.073	3.160	.017	61586.4	.0188
1233	7/29/60	.0000090	.035	1.515	.005	28871.6	.0240

TABLE F-4

1300 SERIES - CLEAR WATER, 2" ALUMINUM PIPE

Run Nº	Date	Kinematic Viscosity Ft.^{2}/Sec.	Discharge, Ft^3/Sec.	Velocity, Ft./Sec.	Hydraulic Gradient, Ft.of H_2O/Ft.	Reynolds Number	Friction Factor
1301	6/23/60	.0000099	.289	12.511	.224	216724.3	.0158
1302	6/23/60	.0000095	.036	1.558	.006	28133.5	.0273
1303	6/24/60	.0000090	.141	6.104	.058	116311.2	.0172
1304	6/24/60	.0000093	.099	4.286	.031	79031.0	.0186
1305	6/24/60	.0000093	.052	2.251	.013	41511.2	.0283
1326	7/28/60	.0000092	.303	13.117	.240	244511.8	.0154
1327	7/28/60	.0000090	.276	11.948	.209	227673.0	.0162
1328	7/28/60	.0000090	.243	10.519	.167	200451.2	.0167
1329	7/28/60	.0000088	.154	6.667	.071	129922.1	.0176
1330	7/28/60	.0000088	.116	5.022	.043	97863.4	.0188
1331	7/29/60	.0000090	.088	3.809	.026	72591.4	.0198
1332	7/29/60	.0000088	.073	3.160	.019	61586.4	.0210
1333	7/29/60	.0000090	.035	1.515	.005	28871.6	.0240

TABLE F-5

1400 SERIES - CLEAR WATER, MODIFIED 2" STEEL PIPE

Run Nº	Date	Kinematic Viscosity Ft.^{2}/Sec.	Discharge, Ft^3/Sec.	Velocity, Ft./Sec.	Hydraulic Gradient, Ft.of H_2O/Ft.	Reynolds Number	Friction Factor
1401	10/3/62	.0000105	.086	3.723	.026	60807.1	.0231
1402	10/3/62	.0000105	.126	5.454	.057	89089.4	.0211
1403	10/3/62	.0000102	.211	9.134	.129	153577.4	.0171
1404	10/3/62	.0000107	.253	10.952	.166	175542.3	.0153
1405	10/2/62	.0000107	.256	11.082	.180	177623.8	.0162
1406	8/9/61	.0000097	.166	7.186	.073	127052.0	.0156
1407	8/9/61	.0000097	.161	6.970	.070	123225.1	.0159
1408	8/9/61	.0000097	.155	6.710	.067	118632.9	.0164
1411	8/9/61	.0000097	.153	6.623	.091	117102.1	.0229
1413	8/9/61	.0000097	.149	6.450	.058	114040.6	.0154
1414	8/9/61	.0000097	.151	6.537	.065	115571.4	.0168
1415	8/9/61	.0000097	.134	5.801	.060	102560.0	.0197

TABLE F-6

1600 SERIES - CLEAR WATER, FLUME 1% SLOPE

Run Nº	Date	Temp., °F.	Kinematic Viscosity Ft^2/Sec. $\times 10^6$	Discharge Ft^3/Sec.	Velocity Ft./Sec.	Upstream Depth, Ft.	Downstream Depth, Ft.	Mean Depth, Ft.	Hydraulic Radius, Ft.	Breadth-to-Depth Ratio
1637	7/28/60	81.0	9.20	.302	3.76	.160	.162	.161	.098	3.109
1638	7/28/60	83.0	8.90	.275	3.69	.149	.149	.149	.093	3.352
1639	7/28/60	83.0	8.90	.243	3.61	.134	.135	.135	.087	3.715
1640	7/28/60	84.0	8.80	.154	3.08	.098	.102	.100	.072	4.979
1641	7/28/60	84.0	8.80	.116	2.53	.092	.092	.092	.067	5.455
1642	7/19/60	82.0	9.00	.087	2.45	.070	.072	.071	.055	7.018
1643	7/19/60	83.0	8.90	.035	1.65	.042	.044	.043	.037	11.650
1644	7/29/60	84.0	8.80	.073	2.28	.062	.065	.064	.051	7.843

(F-6)

Run Nº	Date	Froude Number	Reynolds Number	Friction Factor	Manning's "n"	Bed Factor	Side Factor	King's Constant	Shear Velocity Ft./Sec.	Velocity Ratio
1637	7/28/60	2.73	16020.9	.0178	.008	87.90	.036	11.40	.25	.07
1638	7/28/60	2.83	15415.0	.0176	.008	91.19	.033	11.81	.24	.07
1639	7/28/60	3.01	14123.3	.0172	.008	96.93	.031	12.57	.24	.07
1640	7/28/60	2.93	10066.9	.0196	.008	94.25	.019	12.78	.22	.07
1641	7/28/60	2.17	7708.0	.0269	.010	69.86	.011	9.87	.21	.08
1642	7/19/60	2.62	5991.3	.0236	.009	84.33	.010	12.16	.19	.08
1643	7/19/60	1.97	2743.8	.0350	.010	63.46	.003	10.02	.15	.09
1644	7/29/60	2.53	5280.8	.0253	.009	81.39	.008	11.80	.18	.08

TABLE F-7

1800 SERIES - CLEAR WATER, FLUME 3% SLOPE

Run Nº	Date	Temp., °F.	Kinematic Viscosity Ft^2/Sec. $\times 10^0$	Discharge Ft^3/Sec.	Velocity Ft./Sec.	Upstream Depth, Ft.	Downstream Depth, Ft.	Mean Depth, Ft.	Hydraulic Radius, Ft.	Breadth-to-Depth Ratio
1849	4/1/61	56.0	12.90	.314	5.71	.109	.111	.110	.076	4.546
1850	4/1/61	57.0	12.80	.243	5.23	.093	.092	.093	.068	5.381
1851	4/1/61	57.0	12.80	.231	5.32	.086	.087	.087	.064	5.769
1852	4/1/61	58.0	12.70	.235	5.90	.078	.081	.080	.060	6.283
1853	4/1/61	59.0	12.50	.187	4.84	.076	.078	.077	.059	6.487
1854	4/1/61	60.0	12.20	.169	4.71	.071	.072	.072	.056	6.977
1855	4/1/61	60.0	12.20	.149	4.76	.062	.062	.062	.050	8.000
1856	4/1/61	61.0	12.10	.122	4.42	.053	.057	.055	.045	9.023
1857	4/1/61	62.0	12.00	.266	5.47	.095	.099	.097	.070	5.150

(F-7)

Run Nº	Date	Froude Number	Reynolds Number	Friction Factor	Manning's "n"	Bed Factor	Side Factor	King's Constant	Shear Velocity Ft./Sec.	Velocity Ratio
1849	4/1/61	9.19	13444.3	.0120	.008	295.89	.180	37.68	.22	.04
1850	4/1/61	9.13	11107.4	.0128	.008	294.07	.137	38.16	.21	.04
1851	4/1/61	10.16	10648.0	.0116	.008	327.02	.145	42.13	.20	.04
1852	4/1/61	13.57	11143.9	.0089	.007	436.90	.195	54.68	.20	.03
1853	4/1/61	9.44	9137.9	.0130	.008	303.93	.106	40.05	.19	.04
1854	4/1/61	9.61	8647.9	.0130	.008	309.49	.096	40.59	.19	.04
1855	4/1/61	11.23	7795.1	.0114	.007	361.69	.098	47.93	.18	.04
1856	4/1/61	10.92	6567.8	.0119	.007	351.69	.078	47.35	.17	.04
1857	4/1/61	9.58	12768.0	.0120	.008	308.41	.147	39.01	.21	.04

TABLE F-8

2000 SERIES - SAND-WATER, 1" STEEL PIPE

Run Nº	Date	Concentration % by Volume	Kinematic Viscosity Ft.²/Sec.	Discharge, Ft.³/Sec.	Velocity, Ft./Sec.	Hydraulic Gradient, Ft. of Water per Ft.	Reynolds Nº in Terms of Water Viscosity	Friction Factor
2001	7/21/60	3.333	.0000084	.085	14.168	.490	147413.5	.0137
2002	7/20/60	4.547	.0000084	.063	10.501	.364	109259.4	.0136
2003	7/19/60	4.733	.0000079	.075	12.501	.502	138303.1	.0181
2004	7/19/60	5.460	.0000084	.065	10.834	.377	112728.0	.0191
2005	7/20/60	6.236	.0000082	.010	1.667	.069	17765.8	.1397
2006	7/21/60	6.383	.0000086	.060	10.001	.358	101636.7	.0201
2007	7/19/60	6.540	.0000082	.067	11.168	.377	119030.6	.0170
2008	7/19/60	7.159	.0000079	.038	6.334	.152	70073.6	.0213
2009	7/19/60	7.267	.0000083	.061	10.168	.375	107065.5	.0204
2010	7/19/60	9.211	.0000083	.030	5.000	.124	52655.1	.0279
2011	7/21/60	9.398	.0000087	.074	12.334	.490	123911.1	.0181
2012	7/20/60	12.422	.0000083	.071	11.834	.473	124617.2	.0190
2013	7/21/60	13.355	.0000087	.070	11.668	.473	117213.2	.0195
2014	7/22/60	14.239	.0000072	.046	7.667	.239	93072.9	.0229
2015	7/22/60	16.006	.0000075	.059	9.834	.368	114601.0	.0214
2016	7/25/60	16.989	.0000094	.024	4.000	.178	37194.7	.0625
2017	7/22/60	20.032	.0000075	.069	11.501	.443	134024.9	.0188
2018	7/25/60	20.622	.0000095	.067	11.168	.473	102742.2	.0213
2019	8/12/60	20.622	.0000065	.032	5.334	.185	71719.0	.0366
2020	7/26/60	24.255	.0000079	.066	11.001	.478	121706.7	.0222
2021	7/25/60	25.139	.0000079	.053	8.834	.349	97734.2	.0251
2022	8/12/60	26.121	.0000065	.041	6.834	.248	91890.0	.0299
2023	8/12/60	28.478	.0000080	.050	8.334	.320	91049.5	.0259
2024	7/26/60	29.656	.0000089	.065	10.834	.177	106395.0	.0229
2025	8/12/60	30.246	.0000075	.048	8.001	.322	93234.7	.0283
2026	8/12/60	31.031	.0000065	.042	7.001	.310	94131.2	.0356
2027	8/12/60	32.111	.0000068	.045	7.501	.335	96405.4	.0335
2028	7/26/60	32.111	.0000083	.066	11.001	.484	115841.3	.0225
2029	8/12/60	33.977	.0000072	.041	6.834	.387	82956.2	.0466
2030	7/25/60	34.566	.0000082	.061	10.168	.466	108371.1	.0253

TABLE F-9

2100 SERIES - SAND-WATER, 1" ALUMINUM PIPE

Run Nº	Date	Concentration % by Volume	Kinematic Viscosity Ft.²/ Sec.	Discharge, Ft.³/Sec.	Velocity, Ft./Sec.	Hydraulic Gradient, Ft. of Water per Ft.	Reynolds Nº in Terms of Water Viscosity	Friction Factor
2101	7/21/60	3.338	.0000084	.085	14.168	.522	147413.5	.015
2102	7/20/60	4.547	.0000084	.063	10.501	.390	109259.4	.020
2103	7/19/60	4.733	.0000079	.075	12.501	.512	138303.1	.018
2104	7/19/60	5.460	.0000084	.065	10.834	.392	112728.0	.019
2105	7/20/60	6.236	.0000082	.010	1.667	.072	17765.8	.146
2106	7/21/60	6.383	.0000086	.060	10.001	.373	101636.7	.021
2107	7/19/60	6.540	.0000082	.067	11.168	.406	119030.6	.018
2108	7/19/60	7.159	.0000079	.038	6.334	.152	70073.6	.021
2109	7/19/60	7.267	.0000083	.061	10.168	.582	107065.5	.032
2110	7/19/60	9.211	.0000083	.030	5.000	.186	52655.1	.042
2111	7/21/60	9.398	.0000087	.074	12.334	.460	123911.1	.017
2112	7/20/60	12.422	.0000083	.071	11.834	.498	124617.2	.020
2113	7/21/60	13.355	.0000087	.070	11.668	.510	117213.2	.021
2114	7/22/60	14.239	.0000072	.046	7.667	.262	93072.9	.025
2115	7/22/60	16.006	.0000075	.059	9.834	.389	114601.0	.023
2116	7/25/60	16.989	.0000094	.024	4.000	.162	37194.7	.057
2117	7/22/60	20.032	.0000075	.069	11.501	.477	134024.9	.020
2118	7/25/60	20.622	.0000095	.067	11.168	.507	102742.2	.023
2119	8/12/60	20.622	.0000065	.032	5.334	.259	71719.0	.051
2120	7/26/60	24.255	.0000079	.066	11.001	.491	121706.7	.023
2121	7/26/60	25.139	.0000079	.053	8.834	.348	97734.2	.025
2122	8/12/60	26.121	.0000065	.041	6.834	.241	91890.0	.029
2123	8/12/60	28.478	.0000080	.050	8.334	.323	91049.5	.026
2124	7/26/60	29.656	.0000089	.065	10.834	.483	106395.0	.023
2125	8/12/60	30.246	.0000075	.048	8.001	.325	93234.7	.029
2126	8/12/60	31.031	.0000065	.042	7.001	.311	94131.2	.036
2127	8/12/60	32.111	.0000068	.045	7.501	.277	96405.4	.028
2128	7/26/60	32.111	.0000083	.066	11.001	.515	115841.3	.024
2129	8/12/60	33.977	.0000072	.041	6.834	.351	82956.2	.042
2130	7/25/60	34.566	.0000082	.061	10.168	.556	108371.1	.030

TABLE F - 10

2200 SERIES - SAND-WATER, 2" STEEL PIPE

Run Nº	Date	* Bed Condition	Concentration % by Vol.	Kinematic Viscosity Ft²/Sec.	Discharge Ft³/Sec.	Velocity, Ft./Sec.	Hydraulic Gradient, Ft. Water per Ft.	Reynolds Nº in Terms of Water Viscosity	Friction Factor
2201	7/ 5/60	1	1.216	.0000090	.070	3.030	.028	57743.3	.033[illegible]
2202	7/ 7/60		1.226	.0000094	.112	4.848	.042	83457.9	.0197
2203	7/ 7/60		1.226	.0000094	.199	8.615	.115	157170.7	.0171
2204	7/ 6/60	1	1.463	.0000090	.090	3.896	.034	74241.4	.0247
2206	7/ 5/60		3.164	.0000090	.120	5.195	.052	98988.6	.0213
2207	7/ 4/60		3.460	.0000094	.294	12.727	.242	232201.9	.0165
2208	7/14/60	1, 2	3.658	.0000086	.082	3.550	.055	70788.3	.04[illegible]2
2209	7/14/60	1, 2	3.955	.0000079	.103	4.459	.058	96795.8	.0322
2210	7/ 7/60	1, 2	4.143	.0000088	.105	4.545	.047	88583.5	.0251
2211	7/14/60	1, 2	4.330	.0000085	.088	3.809	.056	76861.7	.0426
2212	7/15/60		4.578	.0000086	.287	12.424	.234	247759.2	.0167
2213	6/29/60	2	5.487	.0000095	.206	8.918	.125	160986.7	.0173
2214	7/ 7/60		5.497	.0000088	.286	12.381	.227	241284.7	.0163
2215	7/ 7/60		5.616	.0000087	.255	11.039	.204	217601.2	.0185
2216	7/14/60	2	6.090	.0000074	.169	7.316	.096	169551.4	.0198
2217	7/15/60		6.090	.0000088	.202	8.744	.182	170417.8	.0263
2218	6/30/60	2	6.288	.0000092	.191	8.268	.130	154131.7	.0210
2219	7/ 8/60		7.336	.0000088	.120	5.195	.050	101238.3	.0204
2220	7/15/60		7.613	.0000084	.286	12.381	.231	252774.4	.0166
2221	8/ 3/60		12.853	.0000080	.171	7.402	.112	158691.1	.0226
2222	8/ 3/60		14.534	.0000085	.233	10.086	.191	203508.9	.0207
2223	8/ 3/60	1	15.226	.0000078	.103	4.459	.095	98036.8	.0527
2224	8/ 4/60	1	16.412	.0000084	.115	4.978	.092	101640.1	.0410
2225	8/ 3/60		17.203	.0000083	.185	8.009	.135	165477.9	.0232
2226	8/ 4/60		18.587	.0000089	.233	10.086	.192	194362.4	.0208
2227	8/ 5/60	1	20.169	.0000081	.133	5.757	.098	121902.6	.0326
2228	8/ 5/60		21.355	.0000082	.155	6.710	.122	140334.4	.0299
2229	8/ 5/60	1	24.124	.0000085	.119	5.151	.115	103938.0	.0478
2230	8/ 5/60		25.211	.0000087	.163	7.056	.138	139096.0	.0306
2231	8/ 4/60		26.200	.0000080	.215	9.307	.202	199523.9	.0257
2232	8/ 9/60		27.189	.0000088	.183	7.922	.153	154388.4	.0269
2233	8/10/60		28.375	.0000087	.170	7.359	.152	145069.5	.0310
2234	8/10/60		29.858	.0000087	.171	7.402	.152	145922.8	.0306
2235	8/11/60	1	29.858	.0000078	.154	6.667	.153	146579.2	.0380
2236	8/ 4/60		30.847	.0000082	.202	8.744	.202	182887.4	.0291
2237	8/11/60		32.033	.0000087	.138	5.974	.136	117762.3	.0420
2238	8/11/60		32.923	.0000080	.206	8.918	.206	191171.7	.0286
2239	8/11/60		33.615	.0000074	.147	6.364	.166	147479.6	.0452

* 1 = Bed in Pipe
2 = Antidune in Flume

NOTE: Runs 2201 - 2220 used Flume
Runs 2221 - 2239 used 2" Return Pipe

TABLE F - 11

2300 SERIES - SAND-WATER, 2" ALUMINUM PIPE

Run Nº	Date	* Bed Condition	Concentration % by Vol.	Kinematic Viscosity Ft.²/Sec.	Discharge Ft.³/Sec.	Velocity, Ft./Sec.	Hydraulic Gradient, Ft. Water per Ft.	Reynolds Nº in Terms of Water Viscosity	Friction Factor
2301	7/ 5/60	1	1.216	.0000090	.070	3.030	.032	57743.2	.0335
2302	7/ 7/60		1.226	.0000094	.112	4.848	.047	88457.6	.0221
2303	7/ 7/60		1.226	.0000094	.199	8.615	.116	157170.2	.0172
2304	7/ 6/60	1	1.463	.0000090	.090	3.896	.037	74241.2	.0269
2305	7/13/60	1, 2	1.289	.0000086	.036	1.558	.057	31077.7	.2590
2306	7/ 5/60		3.164	.0000090	.120	5.195	.051	98988.3	.0209
2307	7/ 4/60		3.460	.0000094	.294	12.727	.235	232201.2	.0160
2308	7/14/60	1, 2	3.658	.0000086	.082	3.550	.058	70788.1	.0508
2309	7/14/60	1, 2	3.955	.0000079	.103	4.459	.062	96795.5	.0344
2310	7/ 7/60	1, 2	4.143	.0000088	.105	4.545	.048	88583.2	.0256
2311	7/14/60	1, 2	4.330	.0000085	.088	3.809	.055	76861.5	.0418
2312	7/15/60		4.578	.0000086	.287	12.424	.234	247758.4	.0167
2313	6/29/60	2	5.487	.0000095	.206	8.918	.136	160986.2	.0189
2314	7/ 7/60		5.497	.0000088	.286	12.381	.227	241283.9	.0163
2315	7/ 7/60		5.616	.0000087	.255	11.039	.186	217603.5	.0168
2316	7/14/60	2	6.090	.0000074	.169	7.316	.094	169550.9	.0194
2317	7/15/60		6.090	.0000088	.202	8.744	.125	170417.3	.0180
2318	6/30/60	2	6.288	.0000092	.191	8.268	.132	153131.1	.0213
2319	7/ 8/60		7.336	.0000088	.120	5.195	.070	101238.0	.0286
2320	7/15/60		7.613	.0000084	.286	12.381	.224	252773.6	.0161
2321	8/ 3/60		12.853	.0000080	.171	7.402	.114	158690.6	.0230
2322	8/ 3/60		14.531	.0000085	.233	10.086	.194	203508.2	.0210
2323	8/ 3/60	1	15.226	.0000078	.103	4,459	.099	98036.5	.0549
2324	8/ 4/60	1	16.412	.0000084	.115	4.978	.089	101639.7	.0396
2325	8/ 3/60		17.203	.0000083	.185	8.009	.138	165477.4	.0237
2326	8/ 4/60		18.587	.0000089	.233	10.086	.193	194361.8	.0209
2327	8/ 5/60	1	20.169	.0000081	.133	5.757	.101	121902.2	.0336
2328	8/ 5/60		21.355	.0000082	.155	6.710	.122	140334.0	.0299
2329	8/ 5/60	1	24.124	.0000085	.119	5.151	.119	103937.7	.0495
2330	8/ 5/60		25.211	.0000087	.163	7.056	.143	139095.6	.0317
2331	8/ 4/60		26.200	.0000080	.215	9.307	.205	199523.2	.0261
2332	8/ 9/60		27.189	.0000088	.183	7.922	.159	154387.9	.0280
2333	8/10/60		28.375	.0000087	.170	7.359	.151	145069.0	.0308
2334	8/10/60		29.858	.0000087	.171	7.402	.152	145922.4	.0306
2335	8/11/60	1	29,858	.0000078	.154	6.667	.156	146578.8	.0387
2336	8/ 4/60		30.847	.0000082	.202	8.744	.209	182886.9	.0302
2337	8/11/60		32.033	.0000087	.138	5.974	.143	117761.9	.0442
2338	8/11/60		32.923	.0000080	.206	8.918	.220	191171.1	.0305
2339	8/11/60		32.923	.0000074	.147	6.364	.179	147479.1	.0488

* 1 — Bed in Pipe
2 — Antidune in Flume

NOTE: Runs 2301 - 2320 used Flume
Runs 2321 - 2339 used 2" Return Pipe

TABLE F - 12

2800 SERIES - SAND-WATER, FLUME 3% SLOPE

(a)

Run Nº	Date	Bed Type*	Concentr'n. % by Volume	Kinematic Viscosity $\times 10^5$ Ft²/Sec.	Discharge Ft³/Sec.	Velocity Ft./Sec.	Upstream Depth, Ft.	Downstream Depth, Ft.	Mean Depth, Ft.
2818	6/30/60	1	6.288	.92	.191	4.02	.095	.095	.095
2807	7/ 4/60	2	3.460	.94	.294	5.50	.107	.107	.107
2806	7/ 5/60	2	3.164	.90	.120	3.87	.062	.062	.062
2804	7/ 6/60	4	1.463	.90	.090	3.46	.052	.052	.052
2803	7/ 7/60	2	1.226	.94	.199	4.63	.086	.087	.086
2802	7/ 7/60	2	1.226	.94	.112	3.93	.057	.058	.057
2810	7/ 7/60	1	4.143	.88	.105	3.56	.060	.058	.059
2815	7/ 7/60	2	5.616	.87	.255	5.05	.102	.101	.101
2814	7/ 7/60	2	5.497	.88	.286	5.20	.109	.110	.110
2850	6/29/60	1	7.941	.94	.206	4.38	.094	.094	.094
2851	6/30/60	1	5.934	.92	.206	4.34	.095	.095	.095
2852	6/30/60	3	6.102	.91	.283	4.72	.120	.120	.120
2853	7/ 5/60	4	1.137	.90	.070	3.11	.045	.045	.045
2854	7/ 7/60	2	3.818	.88	.132	3.94	.068	.067	.067
2855	7/ 7/60	1	6.102	.85	.168	4.05	.083	.083	.083
2856	7/ 7/60	2	8.555	.85	.285	4.91	.116	.116	.116
2857	7/ 7/60	2	7.022	.85	.278	5.06	.110	.110	.110

(F - 12)

(b)

Run Nº	Hydraulic Radius, Ft.	Breadth-to-Depth Ratio	Froude Number	Reynolds Number for Water Viscosity	Friction Factor	Manning's "n"	King's Constant	Shear Velocity Ft./Sec.	Velocity Ratio
2818	.069	5.263	5.29	120630.0	.0220	.009	12.22	.21	.05
2807	.076	4.673	8.77	177710.6	.0130	.007	18.85	.22	.04
2806	.050	8.054	7.51	86022.2	.0172	.008	17.43	.18	.05
2804	.043	9.677	7.16	66162.7	.0185	.007	17.09	.17	.05
2803	.064	5.797	7.74	126039.2	.0154	.007	17.36	.20	.04
2802	.047	8.696	8.42	78600.0	.0157	.007	19.68	.17	.04
2810	.048	8.451	6.67	77650.9	.0195	.008	15.72	.18	.05
2815	.072	4.938	7.84	167172.4	.0145	.007	16.89	.22	.04
2814	.076	4.563	7.63	179636.4	.0145	.007	16.37	.22	.04
2850	.068	5.310	6.35	126827.2	.0182	.008	14.44	.21	.05
2851	.069	5.263	6.15	130110.0	.0189	.008	13.95	.21	.05
2852	.081	4.167	5.76	167945.9	.0188	.008	12.76	.23	.05
2853	.038	11.111	3.36	52541.3	.0202	.008	16.38	.16	.05
2854	.053	7.407	7.20	94918.2	.0176	.008	16.54	.18	.05
2855	.062	6.000	6.13	118106.4	.0195	.008	13.88	.20	.05
2856	.079	4.317	6.47	182685.2	.0169	.008	13.94	.23	.05
2857	.076	4.545	7.21	180790.6	.0153	.007	15.45	.22	.04

* 1 = Antidune
2 = Clean Bed
3 = Jerking Bed
4 = Partial Bed

TABLE F-13

2900 SERIES - SAND-WATER, FLUME 4% SLOPE

(a)

Run Nº	Date	*Bed Type	Concentr'n. % by Volume	Kinematic Viscosity $\times 10^5$ Ft²/Sec.	Discharge Ft³/Sec.	Velocity Ft./Sec.	Upstream Depth, Ft.	Downstream Depth, Ft.	Mean Depth, Ft.
2909	7/14/60	1	3.955	.79	.103	3.75	.055	.055	.055
2912	7/15/60	2	4.578	.86	.286	5.83	.098	.097	.098
2917	7/15/60	2	6.090	.88	.201	5.16	.077	.079	.078
2920	7/15/60	2	7.613	.84	.286	5.72	.100	.100	.100
2919	7/ 8/60	2	7.336	.88	.120	3.58	.067	.067	.067
2958	7/ 8/60	2	6.725	.88	.284	5.74	.100	.097	.099
2960	7/14/60	1	4.352	.85	.082	3.22	.052	.050	.051
2963	7/14/60	2	6.102	.87	.169	4.97	.070	.067	.068
2964	7/15/60	1	5.489	.87	.169	4.90	.069	.068	.069

(F - 13)

(b)

Run Nº	Hydraulic Radius, Ft.	Breadth-to-Depth Ratio	Froude Number	Reynolds Number for Water Viscosity	Friction Factor	Manning's "n"	King's Constant	Shear Velocity Ft./Sec.	Velocity Ratio
2909	.045	9.091	7.94	85420.3	.0165	.010	17.98	.17	.05
2912	.070	5.106	10.79	189879.1	.0106	.009	22.33	.21	.04
2917	.059	6.417	10.62	138408.6	.0114	.009	22.79	.19	.04
2920	.071	5.000	10.16	193322.9	.0112	.009	21.02	.21	.04
2919	.053	7.463	5.95	86293.6	.0213	.010	14.00	.18	.05
2958	.071	5.063	10.32	185148.6	.0111	.008	21.61	.21	.04
2960	.042	9.836	6.30	63563.3	.0209	.010	15.10	.16	.05
2963	.054	7.317	11.28	123393.1	.0113	.007	24.40	.19	.04
2964	.054	7.246	10.81	121655.2	.0116	.008	23.46	.19	.04

* 1 = Antidune
2 = Clean Bed
3 = Jerking Bed
4 = Partial Bed

TABLE F - 14

3200 SERIES - SLUDGE, 2" STEEL PIPE

(a)

Run Nº	Date	Concentr'n. % by Volume	Apparent Kinematic Viscosity of Sludge Ft²/Sec.	Discharge, Ft³/Sec.	Velocity, Ft./Sec.	Hydraulic Gradient, Ft. H_2O/Ft.	Reynolds Number in Terms of Sludge Viscosity	Friction Factor	Kinematic Viscosity of Water at Operating Temperature Ft²/Sec.
3203	3/ 8/61	1.290	.0000137	.308	13.333	.255	166907.2	.016	.0000105
3204	3/ 9/61	1.260	.0000137	.295	12.770	.205	159862.4	.014	.0000105
3206	3/ 9/61	1.230	.0000137	.204	8.831	.162	110548.9	.023	.0000105
3209	3/10/61	1.150	.0000135	.312	13.506	.240	171579.7	.015	.0000105
3205	3/10/61	1.150	.0000135	.337	14.589	.240	185328.0	.012	.0000105
3210	3/11/61	1.150	.0000135	.304	13.160	.222	167180.2	.014	.0000105
3207	3/11/61	1.150	.0000135	.293	12.684	.222	161130.9	.015	.0000105
3211	3/11/61	1.150	.0000135	.277	11.991	.200	152331.9	.015	.0000105
3213	3/11/61	1.180	.0000136	.295	12.770	.222	161037.9	.015	.0000105
3217	3/11/61	1.120	.0000135	.191	8.268	.117	105037.6	.019	.0000105
3219	3/11/61	1.130	.0000136	.127	5.498	.051	69328.2	.019	.0000105
3220	3/11/61	1.150	.0000136	.403	17.446	.242	219994.2	.009	.0000105
3236	3/21/61	1.030	.0000130	.253	10.952	.169	144484.8	.016	.0000098
3228	3/28/61	.780	.0000135	.376	16.277	.329	206775.5	.014	.0000105
3239	3/28/61	1.050	.0000135	.316	13.679	.239	173779.4	.014	.0000105
3240	3/28/61	.970	.0000135	.271	11.731	.172	149032.3	.014	.0000104
3241	3/28/61	.880	.0000135	.181	7.835	.091	99538.2	.016	.0000104
3243	3/28/61	1.100	.0000135	.350	15.151	.298	192477.2	.014	.0000105
3244	3/28/61	1.100	.0000129	.350	15.151	.259	201429.6	.012	.0000099
3246	3/28/61	.970	.0000125	.208	9.004	.119	123537.4	.016	.0000095
3247	3/28/61	.900	.0000125	.179	7.749	.090	106313.4	.017	.0000095
3248	3/28/61	1.000	.0000125	.149	6.450	.049	88495.5	.013	.0000095
3288	4/ 9/61	2.290	.0000143	.307	13.290	.262	159385.0	.016	.0000107
3289	4/ 9/61	2.450	.0000137	.306	13.247	.189	165823.4	.012	.0000098
3290	4/10/61	2.450	.0000137	.273	11.818	.203	147940.5	.016	.0000098
3292	4/10/61	2.350	.0000137	.151	6.537	.078	81827.9	.020	.0000098
3293	4/10/61	2.130	.0000137	.058	2.511	.017	31430.6	.030	.0000097
3294	4/10/61	2.660	.0000142	.264	11.428	.247	138025.9	.021	.0000092
3296	4/10/61	2.660	.0000142	.310	13.420	.300	162075.9	.018	.0000092
3297	4/11/61	2.660	.0000142	.310	13.420	.300	162075.9	.018	.0000092
3298	4/11/61	2.660	.0000142	.269	11.645	.208	140640.0	.017	.0000092
3299	4/11/61	2.670	.0000137	.255	11.039	.192	138186.2	.017	.0000097
3200	4/11/61	2.670	.0000137	.236	10.216	.169	127890.0	.018	.0000097
3201	4/11/61	2.670	.0000137	.211	9.134	.139	114342.3	.018	.0000097
3202	4/11/61	2.670	.0000137	.184	7.965	.106	99710.8	.018	.0000097
3208	4/11/61	2.670	.0000137	.143	6.190	.068	77492.6	.020	.0000097
3242	4/11/61	2.540	.0000137	.104	4.502	.039	56358.3	.021	.0000097
3221	5/12/61	2.630	.0000138	.146	6.320	.060	78545.0	.017	.0000091
3212	5/12/61	2.600	.0000137	.175	7.576	.089	94833.7	.017	.0000091
3214	5/12/61	2.600	.0000137	.243	10.519	.164	131683.3	.016	.0000091

...... Cont'd.

(b)

(F - 14) - Continued

Run Nº	Date	Concentr'n. % by Volume	Apparent Kinematic Viscosity of Sludge Ft²/Sec.	Discharge, Ft³/Sec.	Velocity, Ft./Sec.	Hydraulic Gradient, Ft. H_2O/Ft.	Reynolds Number in Terms of Sludge Viscosity	Friction Factor	Kinematic Viscosity of Water at Operating Temperature Ft²/Sec.
3215	5/12/61	2.440	.0000137	.200	8.658	.112	108381.3	.016	.0000098
3216	5/12/61	2.440	.0000137	.167	11.558	.200	144689.1	.017	.0000098
3222	5/12/61	2.440	.0000137	.261	11.299	.174	141437.6	.015	.0000098
3218	5/12/61	2.440	.0000137	.266	11.515	.200	144147.1	.017	.0000098
3224	5/16/61	2.740	.0000138	.317	13.723	.274	170539.6	.016	.0000091
3225	5/16/61	2.740	.0000138	.309	13.376	.267	166235.7	.016	.0000091
3226	5/16/61	2.790	.0000137	.264	11.428	.210	143063.3	.018	.0000100
3227	5/16/61	2.790	.0000137	.222	9.610	.181	120303.3	.022	.0000100
3228	5/16/61	2.790	.0000137	.205	8.874	.130	111090.9	.018	.0000100
3229	5/16/61	2.790	.0000137	.164	7.099	.098	88872.7	.021	.0000100
3230	5/16/61	2.790	.0000137	.129	5.584	.058	69905.9	.021	.0000098
3231	5/16/61	2.750	.0000137	.121	5.238	.057	65570.7	.023	.0000098
3251	5/17/61	2.720	.0000143	.265	11.472	.220	137579.8	.018	.0000091
3252	5/17/61	2.720	.0000143	.254	10.995	.209	131869.0	.019	.0000091
3253	5/17/61	2.760	.0000141	.174	7.532	.073	91616.8	.014	.0000098
3254	5/17/61	2.760	.0000141	.137	5.931	.060	72135.1	.019	.0000097
3255	5/17/61	2.760	.0000137	.067	2.900	.020	36307.7	.026	.0000095
3249	5/17/61	2.760	.0000137	.259	11.212	.200	140353.8	.018	.0000095
3250	5/18/61	2.760	.0000137	.239	10.346	.170	129515.7	.018	.0000095
3257	5/18/61	2.660	.0000137	.319	13.809	.282	172868.2	.016	.0000097
3258	5/18/61	2.660	.0000137	.256	11.082	.210	138728.1	.019	.0000097
3259	5/18/61	2.660	.0000137	.225	9.740	.173	121929.0	.020	.0000097
3260	5/18/61	2.660	.0000137	.193	8.355	.138	104588.0	.022	.0000097
3262	5/18/61	2.550	.0000137	.140	6.061	.071	75866.9	.021	.0000097
3263	5/18/61	2.550	.0000137	.111	4.805	.058	60151.6	.028	.0000097
3264	5/18/61	2.550	.0000137	.075	3.247	.026	40643.0	.027	.0000097
3270	5/19/61	2.540	.0000138	.255	11.039	.199	137184.8	.018	.0000092
3271	5/19/61	2.540	.0000138	.223	9.654	.163	119969.5	.019	.0000092
3272	5/19/61	2.540	.0000138	.202	8.744	.123	108671.9	.018	.0000092
3273	5/19/61	2.540	.0000138	.187	8.095	.115	100602.2	.019	.0000092
3274	5/19/61	2.540	.0000138	.155	6.710	.087	83386.9	.021	.0000092
3275	5/19/61	2.540	.0000138	.122	5.281	.050	65633.5	.020	.0000090
3276	5/19/61	1.940	.0000127	.099	4.286	.059	57873.1	.035	.0000090
3283	5/23/61	2.100	.0000117	.264	11.428	.188	167518.6	.016	.0000083
3284	5/23/61	2.100	.0000117	.244	10.563	.195	154827.8	.019	.0000083
3285	5/23/61	2.100	.0000117	.217	9.394	.142	137695.2	.018	.0000083
3286	5/23/61	2.100	.0000117	.188	8.138	.112	119293.6	.019	.0000083
3287	5/23/61	2.100	.0000117	.141	6.104	.065	89470.2	.019	.0000083

TABLE F-15

3600 SERIES - SLUDGE, FLUME 1% SLOPE

(a)

Run Nº	Date	Bed Type	Temp. °F.	Concentr'n. Sludge, % by Volume	Sludge Apparent Kinematic Viscosity, Ft.²/Sec. x 10⁵	Water, Kinematic Viscosity x 10⁵ Oper. Temp.	Sludge, Specific Gravity from Sample	Discharge, Ft.³/Sec.	Velocity, Ft./Sec.
3680	4/ 5/61	2	72.0	.81	1.29	.92	1.01	.365	3.97
3681	4/ 5/61	2	72.0	.81	1.29	.92	1.01	.321	3.71
3682	4/ 5/61	2	73.0	.81	1.29	.91	1.01	.232	3.61
3683	4/ 5/61	2	73.0	.81	1.29	.91	1.01	.202	3.39
3684	4/ 5/61	2	73.0	.81	1.29	.91	1.01	.194	3.48
3688	4/ 9/61	2	69.0	2.29	1.43	1.07	1.04	.307	3.53
3685	4/ 9/61	2	69.0	2.29	1.43	1.07	1.04	.306	3.52
3689	4/ 9/61	2	75.0	2.45	1.37	.98	1.04	.259	3.37
3686	4/10/61	2	75.0	2.45	1.37	.98	1.04	.257	3.34
3690	4/10/61	2	75.0	2.45	1.37	.98	1.04	.273	3.55
3691	4/10/61	2	75.0	2.45	1.37	.98	1.04	.075	1.22
3692	4/10/61	2	75.0	2.35	1.37	.98	1.04	.151	2.85
3693	4/10/61	2	76.0	2.13	1.37	.97	1.04	.058	2.03
3694	4/10/61	2	72.0	2.66	1.42	.92	1.05	.264	3.44
3695	4/10/61	2	72.0	2.66	1.42	.92	1.05	.277	3.50
3696	4/10/61	2	72.0	2.66	1.42	.92	1.05	.310	3.56
3697	4/11/61	2	72.0	2.66	1.42	.92	1.05	.310	3.57
3698	4/11/61	2	72.0	2.66	1.42	.92	1.05	.269	3.40
3699	4/11/61	2	76.0	2.67	1.37	.97	1.05	.255	3.34
3600	4/11/61	2	76.0	2.67	1.37	.97	1.05	.236	3.28
3601	4/11/61	2	76.0	2.67	1.37	.97	1.05	.211	3.18
3602	4/11/61	2	76.0	2.67	1.37	.97	1.05	.184	2.67
3603	4/11/61	2	76.0	2.67	1.37	.97	1.05	.143	2.72
3604	4/11/61	2	76.0	2.54	1.37	.97	1.04	.104	2.55

(b)

Run Nº	Upstream Depth, Ft.	Downstream Depth, Ft.	Mean Depth, Ft.	Hydraulic Radius, Ft.	Breadth-to-Depth Ratio	Froude Number	Reynolds Nº in Terms of Water Viscosity	Reynolds Nº in Terms of Sludge Viscosity
3680	.181	.187	.184	.106	2.721	2.67	183103.5	130585.4
3681	.174	.172	.173	.102	2.885	2.46	164353.0	117213.0
3682	.126	.132	.129	.085	3.884	3.14	134841.8	95120.9
3683	.116	.122	.119	.081	4.196	2.99	120592.1	85068.8
3684	.108	.115	.111	.077	4.494	3.39	117886.2	83160.0
3688	.172	.177	.174	.103	2.871	2.22	135767.5	101588.3
3685	.172	.177	.174	.103	2.871	2.21	135382.4	101300.1
3689	.147	.161	.154	.095	3.243	2.28	130518.4	93363.5
3686	.147	.160	.154	.095	3.252	1.15	129549.0	92670.1
3690	.149	.158	.154	.095	3.252	2.54	137614.3	98439.4
3691	.117	.128	.123	.082	4.082	.38	40765.7	29160.9
3692	.106	.106	.106	.074	4.274	2.39	86202.4	61663.1
3693	.056	.059	.057	.047	8.696	2.22	39324.9	27843.2
3694	.149	.157	.153	.095	3.261	2.40	142087.0	92056.3
3695	.151	.166	.158	.097	3.158	2.40	147482.2	95551.8
3696	.173	.176	.174	.103	2.871	2.26	159560.4	103377.2
3697	.167	.180	.174	.103	2.878	2.27	159650.0	103435.2
3698	.157	.159	.158	.097	3.166	2.28	143433.5	91928.7
3699	.149	.157	.153	.095	3.270	2.26	130727.8	92559.1
3600	.139	.148	.144	.091	3.478	2.32	123084.5	87147.4
3601	.127	.139	.133	.087	3.762	2.36	113943.1	80675.0
3602	.155	.121	.138	.089	3.625	1.61	97991.8	69381.0
3603	.103	.107	.105	.074	4.762	2.19	83032.6	58789.5
3604	.080	.083	.082	.062	6.122	2.46	65068.0	46070.1

(c)

Run Nº	Friction Factor	Manning's "n"	King's Constant in Terms of Water Viscosity	King's Constant in Terms of Sludge Viscosity	Shear Velocity, Ft./Sec.	Velocity Ratio
3680	.0346	.008	6.18	6.72	.26	.07
3681	.0383	.009	5.82	6.33	.26	.07
3682	.0336	.008	7.43	8.11	.23	.06
3683	.0364	.008	7.21	7.86	.23	.07
3684	.0327	.008	8.11	8.85	.22	.06
3688	.0427	.009	5.51	5.92	.26	.07
3685	.0429	.009	5.48	5.89	.26	.07
3689	.0432	.009	5.61	6.10	.25	.07
3686	.0438	.009	5.54	6.02	.25	.07
3690	.0389	.009	6.16	6.69	.25	.07
3691	.2848	.023	1.19	1.29	.23	.19
3692	.0468	.009	6.11	6.64	.22	.08
3693	.0588	.010	6.14	6.80	.17	.09
3694	.0414	.009	5.78	6.44	.25	.07
3695	.0409	.009	5.76	6.42	.25	.07
3696	.0418	.009	5.40	6.02	.26	.07
3697	.0418	.009	5.41	6.03	.26	.07
3698	.0432	.009	5.48	6.11	.25	.07
3699	.0440	.009	5.55	6.05	.25	.07
3600	.0436	.009	5.72	6.24	.24	.07
3601	.0444	.009	5.85	6.38	.24	.07
3602	.0643	.011	4.16	4.54	.24	.09
3603	.0515	.010	5.66	6.17	.22	.08
3604	.0493	.009	6.44	7.03	.20	.08

TABLE F-16

3700 SERIES - SLUDGE, FLUME 2% SLOPE

(a)

Run Nº	Date	Bed Type	Temp. °F.	Concentr'n. Sludge, % by Volume	Sludge, Apparent Kinematic Viscosity $Ft^2/Sec. \times 10^5$	Water, Kinematic Viscosity $\times 10^5$ Oper. Temp.	Sludge, Specific Gravity from Sample	Discharge, $Ft^3/Sec.$	Velocity, Ft./Sec.
3770	4/ 4/61	2	69.0	.87	1.43	1.07	1.01	.306	4.77
3771	4/ 4/61	2	70.0	.85	1.33	1.05	1.01	.270	4.74
3773	4/ 4/61	2	71.0	.85	1.33	1.04	1.01	.223	4.57
3774	4/ 4/61	2	71.0	.85	1.33	1.04	1.01	.179	4.20
3775	4/ 4/61	2	72.0	.85	1.32	.92	1.01	.161	4.26
3776	4/ 4/61	2	72.0	.85	1.32	.92	1.01	.137	3.93
3777	4/ 4/61	2	72.0	.85	1.32	.92	1.01	.098	3.59
3778	4/ 4/61	2	72.0	.85	1.32	.92	1.01	.273	4.79
3779	4/ 4/61	2	72.0	.85	1.32	.92	1.01	.220	4.59
3710	5/12/61	2	70.0	2.63	1.43	1.05	1.04	.033	1.98
3711	5/12/61	2	73.0	2.63	1.38	.91	1.04	.146	3.73
3712	5/12/61	2	73.0	2.60	1.37	.91	1.04	.175	4.11
3714	5/12/61	2	73.0	2.60	1.37	.91	1.04	.243	3.82
3715	5/12/61	2	75.0	2.44	1.37	.98	1.04	.200	4.39
3717	5/12/61	2	75.0	2.44	1.37	.98	1.04	.261	4.56
3718	5/12/61	2	75.0	2.44	1.37	.98	1.04	.266	4.72
3719	5/12/61	2	75.0	2.78	1.37	.98	1.05	.361	4.81
3720	5/12/61	2	75.0	2.78	1.37	.98	1.05	.432	5.21
3721	5/12/61	2	75.0	2.78	1.37	.98	1.05	.502	5.84
3722	5/12/61	2	75.0	2.78	1.37	.98	1.05	.485	5.48
3723	5/12/61	2	76.0	2.78	1.36	.97	1.05	.529	5.74
3716	5/12/61	2	75.0	2.44	1.37	.98	1.04	.267	4.79
3724	5/16/61	2	73.0	2.74	1.38	.91	1.05	.317	4.81
3725	5/16/61	2	73.0	2.74	1.38	.91	1.05	.309	4.97
3726	5/16/61	2	74.0	2.79	1.37	1.00	1.05	.264	4.82
3727	5/16/61	2	74.0	2.79	1.37	1.00	1.05	.222	4.50
3728	5/16/61	2	74.0	2.79	1.37	1.00	1.05	.205	4.48
3729	5/16/61	2	74.0	2.79	1.37	1.00	1.05	.164	4.15
3730	5/16/61	2	75.0	2.79	1.37	.98	1.05	.129	3.86
3731	5/16/61	2	75.0	2.75	1.37	.98	1.05	.121	4.04
3732	5/16/61	2	75.0	2.90	1.37	.98	1.05	.565	5.92
3713	5/16/61	2	75.0	2.90	1.37	.98	1.05	.535	5.60
3700	5/16/61	2	75.0	2.90	1.37	.98	1.05	.565	5.92
3733	5/16/61	2	75.0	2.90	1.37	.98	1.05	.440	5.54
3701	5/16/61	2	75.0	2.90	1.37	.98	1.05	.430	5.42
3734	5/16/61	2	75.0	2.90	1.37	.98	1.05	.440	5.27
3702	5/16/61	2	75.0	2.90	1.37	.98	1.05	.449	5.38
3735	5/16/61	2	75.0	2.90	1.37	.98	1.05	.460	5.76
3736	5/16/61	2	75.0	2.90	1.37	.98	1.05	.412	5.40
3737	5/16/61	2	75.0	2.90	1.37	.98	1.05	.350	4.87
3738	5/16/61	2	75.0	2.90	1.37	.98	1.05	.340	5.02
3739	5/16/61	2	75.0	2.90	1.37	.98	1.05	.306	4.79

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(F - 16) - Continued

(b)

Run Nº	Upstream Depth, Ft.	Downstream Depth, Ft.	Mean Depth, Ft.	Hydraulic Radius, Ft.	Breadth-to-Depth Ratio	Froude Number	Reynolds Nº in Terms of Water Viscosity	Reynolds Nº in Terms of Sludge Viscosity
3770	.128	.128	.128	.085	3.896	5.50	151506.5	113365.0
3771	.113	.114	.114	.078	4.396	6.14	140875.4	111217.4
3773	.096	.099	.097	.070	5.128	6.65	123011.5	96189.5
3774	.083	.087	.085	.064	5.854	6.41	103384.6	80842.1
3775	.074	.077	.076	.058	6.593	7.43	107400.9	74855.2
3775	.074	.077	.076	.058	6.593	7.43	107400.9	74855.2
3776	.068	.072	.070	.054	7.186	6.89	92269.6	64309.1
3777	.052	.057	.055	.045	9.160	7.35	70297.8	48995.5
3778	.113	.116	.114	.078	4.380	6.23	162307.8	113123.6
3779	.094	.097	.096	.069	5.217	6.81	137580.0	95889.1
3710	.032	.035	.034	.030	14.815	3.61	22651.4	16632.2
3711	.077	.080	.078	.060	6.383	5.53	98479.1	64939.1
3712	.083	.087	.085	.063	5.882	6.17	113760.0	75563.2
3714	.148	.107	.127	.084	3.922	3.55	140861.5	93565.0
3715	.088	.093	.091	.067	5.505	6.60	120162.5	85955.6
3717	.116	.113	.115	.079	4.364	5.63	147004.5	105156.5
3718	.113	.113	.113	.078	4.428	6.12	150205.7	107446.4
3719	.149	.151	.150	.094	3.333	4.79	184585.3	132039.1
3720	.166	.166	.166	.100	3.015	5.08	212530.6	152029.2
3721	.170	.174	.172	.102	2.906	6.15	243051.4	173861.6
3722	.173	.181	.177	.104	2.824	5.26	232535.5	166339.3
3723	.183	.185	.184	.106	2.715	5.56	250990.5	179015.3
3716	.111	.113	.112	.077	4.478	6.37	150448.6	107620.2
3724	.134	.129	.132	.086	3.798	5.46	181790.8	119876.5
3725	.126	.123	.125	.083	4.013	6.15	181213.6	119495.9
3726	.113	.107	.110	.076	4.563	6.59	146528.0	106954.7
3727	.099	.098	.099	.071	5.063	6.37	127856.8	93326.1
3728	.091	.092	.092	.067	5.455	6.80	120064.0	87638.0
3729	.078	.080	.079	.060	6.316	6.76	99600.0	72700.7
3720	.066	.067	.067	.053	7.500	6.93	83458.8	59700.4
3731	.059	.061	.060	.048	8.333	8.43	79053.1	56548.9
3732	.192	.189	.191	.108	2.620	5.71	261095.5	186769.1
3713	.192	.189	.191	.108	2.620	5.11	246945.3	176647.0
3700	.192	.189	.191	.108	2.620	5.71	261095.5	186769.1
3733	.160	.157	.159	.097	3.150	6.00	219299.2	156871.0
3701	.160	.157	.159	.097	3.150	5.75	214627.4	153529.1
3734	.167	.167	.167	.100	2.993	5.16	215061.2	153839.4
3702	.167	.167	.167	.100	2.993	5.38	219551.0	157051.1
3735	.160	.159	.160	.097	3.133	6.45	228009.4	163101.6
3736	.154	.151	.152	.095	3.279	5.93	209310.2	149725.6
3737	.144	.143	.144	.091	3.478	5.12	180885.7	129392.7
3738	.136	.135	.135	.088	3.692	5.79	180453.9	129083.8
3739	.128	.127	.127	.084	3.922	5.60	164365.7	117575.5

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(F - 16) - Continued

(c)

Run Nº	Friction Factor	Manning's "n"	King's Constant in Terms of Water Viscosity	King's Constant in Terms of Sludge Viscosity	Shear Velocity Ft./Sec.	Velocity Ratio
3770	.0193	.009	12.69	13.65	.23	.05
3771	.0179	.008	14.05	14.90	.22	.05
3773	.0173	.008	15.44	16.42	.21	.05
3774	.0187	.008	15.20	16.17	.20	.05
3775	.0165	.007	16.90	18.49	.19	.05
3776	.0180	.008	15.94	17.44	.19	.05
3777	.0180	.007	17.34	18.98	.17	.05
3778	.0175	.008	13.82	15.12	.22	.05
3779	.0169	.008	15.22	16.66	.21	.05
3710	.0393	.010	10.24	11.06	.14	.07
3711	.0222	.009	13.04	14.47	.20	.05
3712	.0192	.008	14.14	15.67	.20	.05
3714	.0297	.011	8.32	9.21	.23	.06
3715	.0179	.008	15.14	16.46	.21	.05
3717	.0196	.008	12.78	13.90	.23	.05
3718	.0181	.008	13.81	15.02	.22	.05
3719	.0209	.009	10.76	11.71	.25	.05
3720	.0190	.009	11.17	12.15	.25	.05
3721	.0154	.008	13.17	14.32	.26	.04
3722	.0179	.008	11.45	12.45	.26	.05
3723	.0166	.008	11.93	12.98	.26	.05
3716	.0173	.008	14.29	15.54	.22	.05
3724	.0192	.009	12.00	13.32	.24	.05
3725	.0173	.008	13.41	14.88	.23	.05
3726	.0169	.008	14.80	16.01	.22	.05
3727	.0180	.008	14.59	15.79	.21	.05
3728	.0172	.008	15.57	16.85	.21	.05
3729	.0179	.008	15.86	17.16	.20	.05
3730	.0183	.008	16.38	17.81	.18	.05
3731	.0152	.007	19.78	21.51	.18	.04
3732	.0159	.008	12.16	13.23	.26	.04
3713	.0177	.009	11.03	12.00	.26	.05
3700	.0159	.008	12.16	13.23	.26	.04
3733	.0163	.008	13.00	14.13	.25	.05
3701	.0170	.008	12.51	13.61	.25	.05
3734	.0186	.009	11.34	12.33	.25	.05
3702	.0178	.008	11.75	12.78	.25	.05
3735	.0151	.008	13.83	15.03	.25	.04
3736	.0168	.008	12.99	14.13	.25	.05
3737	.0198	.009	11.45	12.46	.24	.05
3738	.0180	.008	12.90	14.03	.24	.05
3739	.0188	.008	12.64	13.74	.23	.05

TABLE F-17

3800 SERIES - SLUDGE, FLUME 3% SLOPE

(a)

Run No	Date	Bed Type	Temp. °F.	Concent'n. Sludge, % by Volume	Sludge, Apparent Kinematic Viscosity Ft.²/Sec. x 10^5	Water, Kinematic Viscosity x 10^5 Oper. Temp.	Sludge, Specific Gravity from Sample	Discharge, Ft.³/Sec.	Velocity, Ft./Sec.
3861	5/18/61	2	76.0	2.55	1.37	.97	1.04	.170	4.93
3862	5/18/61	2	76.0	2.55	1.37	.97	1.04	.140	4.55
3863	5/18/61	2	77.0	2.55	1.37	.97	1.04	.111	4.25
3864	5/18/61	2	77.0	2.55	1.37	.97	1.04	.075	3.49
3859	4/ 1/61	2	69.0	.92	1.34	1.07	1.02	.333	6.01
3860	4/ 1/61	2	69.0	.92	1.34	1.07	1.02	.301	5.81
3861	4/ 1/61	2	69.0	.92	1.34	1.07	1.02	.273	5.75
3862	4/ 1/61	2	69.0	.92	1.34	1.07	1.02	.247	5.60
3863	4/ 1/61	2	70.0	.92	1.33	1.05	1.02	.232	5.30
3866	4/ 1/61	2	72.0	.80	1.31	.92	1.01	.150	4.80
3867	4/ 1/61	2	72.0	.80	1.31	.92	1.01	.122	4.33
3868	4/ 1/61	2	72.0	.79	1.31	.92	1.01	.274	5.74
3869	4/ 1/61	2	72.0	.79	1.31	.92	1.01	.211	5.48
3840	5/17/61	2	70.0	2.99	1.47	1.05	1.05	.531	6.72
3841	5/17/61	2	70.0	2.99	1.47	1.05	1.05	.456	6.35
3842	5/17/61	2	70.0	2.99	1.47	1.05	1.05	.324	5.50
3843	5/17/61	2	73.0	2.72	1.43	.91	1.05	.265	5.48
3844	5/17/61	2	73.0	2.72	1.43	.91	1.05	.254	5.24
3845	5/17/61	2	73.0	2.72	1.43	.91	1.05	.246	5.80
3846	5/17/61	2	75.0	2.76	1.41	.98	1.05	.174	4.86
3847	5/17/61	2	76.0	2.76	1.41	.97	1.05	.137	4.42
3848	5/17/61	2	78.0	2.76	1.37	.95	1.05	.067	2.89
3849	5/17/61	2	78.0	2.76	1.37	.95	1.05	.259	5.68
3850	5/18/61	2	78.0	2.76	1.37	.95	1.05	.239	5.54
3851	5/18/61	2	72.0	2.81	1.46	.92	1.05	.504	6.33
3852	5/18/61	2	73.0	2.81	1.43	.91	1.05	.441	6.09
3853	5/18/61	2	74.0	2.81	1.42	1.00	1.05	.402	5.94
3854	5/18/61	2	74.0	2.81	1.42	1.00	1.05	.360	5.83
3855	5/18/61	2	74.0	2.81	1.42	1.00	1.05	.324	5.54
3856	5/18/61	2	76.0	2.66	1.37	.97	1.05	.324	5.77
3857	5/18/61	2	76.0	2.66	1.37	.97	1.05	.319	6.05
3858	5/18/61	2	76.0	2.66	1.37	.97	1.05	.256	5.60
3859	5/18/61	2	76.0	2.66	1.37	.97	1.05	.225	5.31
3860	5/18/61	2	76.0	2.66	1.37	1.97	1.05	.193	5.08

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(F - 17) - Continued

(b)

Run Nº	Upstream Depth, Ft.	Downstream Depth, Ft.	Mean Depth, Ft.	Hydraulic Radius, Ft.	Breadth-to-Depth Ratio	Froude Number	Reynolds Nº in Terms of Water Viscosity	Reynolds Nº in Terms of Sludge Viscosity
3861	.066	.072	.069	.054	7.273	10.99	109826.0	77760.0
3862	.060	.063	.062	.049	8.108	10.43	91958.4	65109.2
3863	.050	.054	.052	.043	9.600	10.76	75307.6	53320.0
3864	.042	.044	.043	.037	11.650	8.80	53203.7	37669.8
3859	.109	.113	.111	.077	4.511	10.13	173084.5	138209.3
3860	.102	.106	.104	.073	4.819	10.10	158498.7	126562.4
3861	.093	.097	.095	.069	5.263	10.81	148317.8	118432.8
3862	.086	.091	.088	.065	5.660	11.02	136001.9	108598.5
3863	.086	.089	.087	.065	5.714	9.96	131163.8	103550.4
3866	.062	.063	.062	.050	8.000	11.46	104413.0	73328.2
3867	.055	.057	.056	.046	8.889	10.34	86560.0	60790.2
3868	.095	.078	.077	.059	6.487	10.72	172170.0	120913.3
3869	.076	.078	.077	.059	6.487	12.12	140676.5	98795.7
3840	.158	.157	.158	.097	3.166	8.88	248357.0	177397.8
3841	.142	.146	.144	.091	3.478	8.71	220098.7	157213.3
3842	.116	.120	.118	.080	4.240	7.97	167619.1	119727.9
3843	.095	.098	.097	.070	5.172	9.66	168707.7	107359.4
3844	.095	.099	.097	.070	5.150	8.78	161169.2	102562.2
3845	.083	.087	.085	.063	5.882	12.27	160504.6	102139.3
3846	.070	.073	.072	.056	6.977	10.23	111040.0	77176.7
3847	.061	.063	.062	.050	8.054	9.77	91134.0	62695.0
3848	.049	.043	.046	.039	10.811	5.61	47440.4	32896.6
3849	.086	.097	.091	.067	5.480	10.98	160264.0	111132.0
3850	.082	.090	.086	.064	5.797	11.05	149315.4	103539.9
3851	.157	.161	.159	.097	3.141	7.82	266918.7	168195.3
3852	.144	.146	.145	.092	3.448	7.94	246236.5	156695.9
3853	.133	.137	.135	.088	3.692	8.09	209123.2	147269.9
3854	.120	.127	.123	.083	4.054	3.57	193688.8	136400.6
3855	.114	.120	.117	.080	4.271	8.14	177248.0	124822.5
3856	.110	.115	.113	.078	4.444	9.17	185430.9	131290.5
3857	.103	.108	.105	.074	4.743	10.80	184710.1	130780.2
3858	.088	.094	.091	.067	5.480	10.69	154832.2	109625.7
3859	.081	.088	.085	.063	5.911	10.35	137898.6	97636.2
3860	.072	.079	.076	.058	6.593	10.59	59872.5	86094.0

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(F - 17) - Continued

(c)

Run Nº	Friction Factor	Manning's "n"	King's Constant in Terms of Water Viscosity	King's Constant in Terms of Sludge Viscosity	Shear Velocity Ft./Sec.	Velocity Ratio
3861	.0111	.007	24.38	26.58	.19	.04
3862	.0122	.008	23.57	25.69	.18	.04
3863	.0123	.007	24.20	27.15	.17	.04
3864	.0157	.008	21.32	23.25	.15	.04
3859	.0110	.008	21.97	23.24	.22	.04
3860	.0111	.008	22.07	23.34	.22	.04
3861	.0108	.008	23.74	25.11	.21	.04
3862	.0107	.007	24.44	25.86	.20	.04
3863	.0119	.008	22.35	23.71	.20	.04
3866	.0112	.007	25.56	27.92	.18	.04
3867	.0127	.008	23.58	25.76	.17	.04
3868	.0108	.008	22.78	24.88	.21	.04
3869	.0101	.007	25.96	28.35	.19	.04
3840	.0111	.008	18.66	20.30	.25	.04
3841	.0116	.008	18.54	20.16	.24	.04
3842	.0136	.009	17.60	19.14	.23	.04
3843	.0120	.008	20.54	23.00	.21	.04
3844	.0131	.008	18.96	21.23	.21	.04
3845	.0097	.007	25.83	28.92	.20	.03
3846	.0122	.008	22.81	24.98	.19	.04
3847	.0132	.008	22.40	24.59	.18	.04
3848	.0241	.010	14.27	15.64	.16	.05
3849	.0107	.007	23.55	25.81	.21	.04
3850	.0107	.007	23.86	26.14	.20	.04
3851	.0125	.009	16.15	18.13	.25	.04
3852	.0128	.009	16.51	18.48	.24	.04
3853	.0128	.009	17.39	18.98	.24	.04
3854	.0126	.008	18.49	20.18	.23	.04
3855	.0134	.009	17.75	19.38	.23	.04
3856	.0121	.008	19.56	21.32	.22	.04
3857	.0104	.008	22.93	24.99	.22	.04
3858	.0110	.008	23.12	25.20	.21	.04
3859	.0115	.008	22.50	24.53	.20	.04
3860	.0116	.008	27.86	25.44	.19	.04

TABLE F-18

(a) 3900 SERIES - SLUDGE, FLUME 4% SLOPE

Run №	Date	Bed Type	Temp. °F.	Concentr'n. Sludge, % by Volume	Sludge, Apparent Kinematic Viscosity, Ft²/Sec. x 10^5	Water, Kinematic Viscosity x 10^5 Oper. Temp.	Sludge, Specific Gravity From Sample	Discharge, Ft³/Sec.	Velocity, Ft./Sec.
3938	3/28/61	2	70.0	.78	1.35	1.05	1.01	.376	7.51
3939	3/28/61	2	70.0	1.05	1.35	1.05	1.02	.316	6.80
3940	3/28/61	2	71.0	.97	1.35	1.04	1.02	.271	6.91
3941	3/28/61	2	71.0	.88	1.35	1.04	1.02	.181	5.72
3942	3/28/61	2	71.0	.88	1.35	1.04	1.02	.123	4.99
3943	3/28/61	2	70.0	1.10	1.35	1.05	1.02	.350	6.64
3944	3/28/61	2	75.0	1.10	1.29	.99	1.02	.350	7.78
3946	3/28/61	2	78.0	.97	1.25	.95	1.02	.208	6.06
3947	3/28/61	2	78.0	.90	1.25	.95	1.02	.179	5.92
3948	3/28/61	2	78.0	1.00	1.25	.95	1.02	.149	5.49
3903	3/ 8/61	2	70.0	1.29	1.37	1.05	1.02	.308	6.78
3904	3/ 9/61	2	70.0	1.26	1.37	1.05	1.02	.295	7.20
3906	3/ 9/61	2	70.0	1.23	1.37	1.05	1.02	.204	6.11
3909	3/10/61	2	70.0	1.15	1.35	1.05	1.02	.312	6.71
3905	3/10/61	2	70.0	1.15	1.35	1.05	1.02	.337	7.25
3910	3/11/61	2	70.0	1.15	1.35	1.05	1.02	.304	7.08
3907	3/11/61	2	70.0	1.15	1.35	1.05	1.02	.293	6.83
3911	3/11/61	2	70.0	1.15	1.35	1.05	1.02	.277	6.97
3913	3/11/61	2	70.0	1.18	1.36	1.05	1.02	.295	7.19
3917	3/11/61	2	70.0	1.12	1.36	1.05	1.02	.191	6.29
3919	3/11/61	2	70.0	1.13	1.36	1.05	1.02	.127	5.80
3920	3/11/61	2	70.0	1.15	1.36	1.05	1.02	.403	9.59
3936	3/21/61	2	75.0	1.03	1.30	.98	1.02	.253	6.36
3968	5/19/61	2	76.0	2.93	1.43	.97	1.05	.358	6.90
3970	5/19/61	2	80.0	2.54	1.38	.92	1.04	.255	5.97
3971	5/19/61	2	80.0	2.54	1.38	.92	1.04	.223	5.79
3972	5/19/61	2	80.0	2.54	1.38	.92	1.04	.202	5.57
3973	5/19/61	2	80.0	2.54	1.38	.92	1.04	.187	5.65
3974	5/19/61	2	80.0	2.54	1.38	.92	1.04	.155	5.10
3975	5/19/61	2	82.0	2.54	1.38	.90	1.04	.122	4.84
3976	5/19/61	2	82.0	1.94	1.27	.90	1.03	.099	4.34
3977	5/19/61	2	86.0	2.10	1.23	.85	1.04	.585	8.09
3932	5/19/61	2	86.0	2.10	1.23	.85	1.04	.573	7.92
3978	5/19/61	2	86.0	2.10	1.23	.85	1.04	.468	7.22
3979	5/19/61	2	86.0	2.10	1.23	.85	1.04	.410	6.86
3980	5/19/61	2	86.0	2.10	1.23	.85	1.04	.349	6.19
3981	5/19/61	2	86.0	2.10	1.23	.85	1.04	.321	6.35
3982	5/19/61	2	86.0	2.10	1.23	.85	1.04	.277	5.66
3933	5/19/61	2	86.0	2.10	1.23	.85	1.04	.242	5.16
3983	5/19.61	2	89.0	2.10	1.17	.83	1.04	.264	6.07
3984	5/19/61	2	89.0	2.10	1.17	.83	1.04	.244	5.93
3985	5/19/61	2	89.0	2.10	1.17	.83	1.04	.217	5.81
3986	5/19/61	2	89.0	2.10	1.17	.83	1.04	.188	5.72
3987	5/19/61	2	89.0	2.10	1.17	.83	1.04	.141	4.97
3988	5/19/61	2	89.0	2.10	1.17	.83	1.04	.086	3.96
3969	5/19/61	2	76.0	2.93	1.43	.97	1.05	.315	6.54

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(b)

Run Nº	Upstream Depth, Ft.	Downstream Depth, Ft.	Mean Depth, Ft.	Hydraulic Radius, Ft.	Breadth-to-Depth Ratio	Froude Number	Reynolds Nº in Terms of Water Viscosity	Reynolds Nº in Terms of Sludge Viscosity
3938	.101	.099	.100	.071	5.000	17.53	203235.8	158073.3
3939	.095	.091	.093	.068	5.381	15.45	176126.5	136987.3
3940	.080	.077	.078	.060	6.383	13.92	159392.3	122731.1
3941	.063	.063	.063	.051	7.895	16.05	112219.6	86450.7
3942	.051	.047	.049	.041	10.169	15.71	78641.2	60682.8
3943	.106	.105	.105	.074	4.743	12.99	187156.6	145566.2
3944	.091	.089	.090	.066	5.556	20.87	207360.0	159136.7
3946	.068	.069	.069	.054	7.273	16.57	137717.1	104665.0
3947	.062	.062	.062	.049	8.108	17.05	120034.5	91226.2
3948	.054	.054	.054	.045	9.231	17.26	103964.2	79012.8
3903	.094	.087	.091	.067	5.505	15.70	172974.9	132572.0
3904	.083	.081	.082	.062	6.091	19.60	169986.3	130231.5
3906	.067	.067	.067	.053	7.500	17.11	123424.4	94595.3
3909	.094	.092	.093	.068	5.381	15.06	173872.8	135234.4
3905	.094	.092	.093	.068	5.381	17.56	187757.7	146033.8
3910	.088	.084	.086	.064	5.825	18.16	172714.7	134333.6
3907	.088	.084	.086	.064	5.825	16.89	166570.7	129555.0
3911	.081	.078	.080	.060	6.283	18.93	159200.0	123822.2
3913	.085	.079	.082	.062	6.091	19.57	169868.2	131148.2
3917	.060	.062	.061	.049	8.219	20.22	117488.0	90707.6
3919	.045	.042	.044	.037	11.429	23.89	81766.5	63128.5
3920	.087	.082	.084	.063	5.941	33.90	230064.0	177622.9
3936	.081	.078	.080	.060	6.283	15.78	155755.1	177415.4
3968	.104	.103	.104	.073	4.819	14.23	207560.8	140793.0
3970	.085	.086	.085	.064	5.854	12.94	166010.4	110673.6
3971	.077	.077	.077	.059	6.487	13.49	148423.5	98949.0
3972	.072	.072	.072	.056	6.897	13.30	135641.7	90427.8
3973	.066	.067	.066	.052	7.547	14.95	127693.9	85129.3
3974	.059	.062	.061	.049	8.219	13.29	108716.1	72477.4
3975	.049	.052	.050	.042	9.917	14.43	90346.7	58921.7
3976	.044	.047	.046	.039	10.909	12.76	75209.3	53298.0
3977	.141	.148	.145	.092	3.458	14.05	350119.5	241952.5
3932	.141	.148	.145	.092	3.458	13.48	342976.0	237015.9
3978	.126	.133	.130	.085	3.859	12.49	288760.0	199549.6
3979	.117	.122	.120	.081	4.181	12.24	261639.5	180807.8
3980	.112	.114	.113	.078	4.428	10.52	227025.9	156887.8
3981	.102	.101	.101	.072	4.938	12.35	215017.4	148589.3
3982	.103	.093	.098	.070	5.106	10.14	186282.4	128731.7
3933	.094	.093	.094	.068	5.333	8.82	165152.0	114129.4
3983	.088	.087	.087	.065	5.742	13.13	190081.9	134844.4
3984	.082	.083	.082	.062	6.061	13.22	177095.9	125632.1
3985	.074	.075	.075	.057	6.704	14.05	159545.1	113181.5
3986	.066	.066	.066	.052	7.595	15.44	143344.6	101688.9
3987	.055	.058	.057	.046	8.824	13.53	110134.0	78129.2
3988	.042	.044	.043	.037	11.538	11.23	70576.4	50067.0
3969	.097	.096	.096	.069	5.195	13.80	136086.6	126226.6

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(c)

Run Nº	Friction Factor	Manning's "n"	King's Constant in Terms of Water Viscosity	King's Constant in Terms of Sludge Viscosity	Shear Velocity Ft./Sec.	Velocity Ratio
3938	.0065	.007	35.85	38.17	.21	.03
3939	.0076	.007	32.36	34.45	.21	.03
3940	.0065	.006	39.56	42.23	.20	.03
3941	.0080	.007	35.23	37.60	.18	.03
3942	.0085	.007	35.62	38.02	.16	.03
3943	.0086	.008	27.49	29.27	.22	.03
3944	.0056	.006	41.67	44.52	.21	.03
3946	.0076	.007	34.75	37.21	.19	.03
3947	.0075	.007	36.04	38.60	.18	.03
3948	.0077	.007	37.35	40.00	.17	.03
3903	.0075	.007	32.88	35.14	.21	.03
3904	.0062	.006	40.54	43.33	.20	.03
3906	.0073	.007	37.29	39.85	.18	.03
3909	.0078	.007	31.64	33.69	.21	.03
3905	.0067	.007	36.19	38.53	.21	.03
3910	.0066	.007	37.60	40.04	.20	.03
3907	.0071	.007	35.29	37.58	.20	.03
3911	.0064	.007	39.24	41.78	.20	.03
3913	.0062	.006	40.49	43.19	.20	.03
3917	.0064	.006	43.10	45.98	.18	.03
3919	.0057	.006	.51.80	55.26	.15	.03
3920	.0035	.005	65.35	69.72	.20	.02
3936	.0076	.007	32.90	35.30	.20	.03
3968	.0079	.008	29.07	32.03	.22	.03
3970	.0093	.008	27.25	30.16	.20	.03
3971	.0091	.008	28.51	31.55	.19	.03
3972	.0093	.008	28.53	31.68	.19	.03
3973	.0084	.007	31.89	35.29	.18	.03
3974	.0097	.008	28.89	31.97	.18	.03
3975	.0092	.007	31.95	35.55	.16	.03
3976	.0107	.008	28.68	31.26	.16	.04
3977	.0072	.007	26.67	29.25	.24	.03
3932	.0076	.008	25.72	28.21	.24	.03
3978	.0084	.008	24.38	26.74	.23	.03
3979	.0089	.008	24.19	26.53	.23	.03
3980	.0105	.009	21.40	23.48	.22	.04
3981	.0092	.008	25.05	27.47	.22	.03
3982	.0113	.009	21.10	23.14	.21	.04
3933	.0132	.010	18.74	20.56	.21	.04
3983	.0091	.008	26.73	29.12	.20	.03
3984	.0091	.008	27.21	29.65	.20	.03
3985	.0087	.008	28.72	31.29	.19	.03
3986	.0082	.007	31.77	34.62	.18	.03
3987	.0096	.008	28.75	31.32	.17	.03
3988	.0122	.008	25.60	27.90	.15	.04
3969	.0083	.008	28.71	31.64	.21	.03

TABLE F-19

4200 SERIES - FINES-WATER SLURRY, 2" STEEL PIPE

Run Nº	Date	Concentr'n. % by Volume	Apparent Kinematic Viscosity of Fines-Water Slurry, Ft.²/Sec.	Discharge, Ft.³/Sec.	Velocity, Ft./Sec.	Hydraulic Gradient, Ft. of H_2O per Ft.	Reynolds Number in Terms of Slurry Apparent Viscosity	Friction Factor
4202	7/13/61	12.380	.0000372	.230	9.957	.212	19468.8	.024
4204	7/13/61	12.380	.0000370	.234	10.130	.200	46952.5	.022
4205	7/13/61	12.380	.0000371	.229	9.913	.241	45825.4	.027
4206	7/13/61	12.380	.0000371	.220	9.524	.246	44024.4	.030
4210	7/14/61	37.400	.0000999	.153	6.623	.098	11370.3	.025
4211	7/14/61	13.010	.0000389	.234	10.130	.170	44659.2	.018
4212	7/14/61	13.130	.0000392	.227	9.827	.219	42991.7	.025
4213	7/20/61	13.030	.0000387	.227	9.827	.192	43547.2	.022
4215	7/20/61	13.280	.0000400	.219	9.480	.210	40647.1	.026
4216	7/20/61	9.310	.0000296	.232	10.043	.200	58189.0	.022
4217	7/20/61	9.350	.0000295	.205	8.874	.151	51591.3	.021
4218	7/20/61	5.850	.0000192	.201	8.701	.144	77721.3	.021
4219	7/20/61	9.440	.0000296	.188	8.138	.139	47153.2	.023
4220	7/20/61	9.390	.0000293	.171	7.402	.113	43328.5	.023
4221	7/20/61	9.300	.0000290	.160	6.296	.099	40960.7	.023
4222	7/20/61	9.230	.0000285	.139	6.017	.091	36208.9	.028
4223	7/20/61	9.220	.0000287	.108	4.675	.060	27937.5	.030
4224	7/20/61	9.200	.0000286	.075	3.247	.025	19468.8	.026
4225	7/20/61	9.010	.0000281	.039	1.688	.025	10303.9	.097
4226	7/20/61	8.550	.0000262	.041	1.775	.024	11617.9	.084
4227	7/20/61	9.310	.0000285	.129	5.584	.067	33603.9	.024
4228	7/20/61	9.280	.0000285	.166	7.186	.092	43242.2	.020
4229	7/20/61	9.340	.0000285	.186	8.052	.104	48452.2	.018
4230	7/20/61	9.300	.0000285	.211	9.134	.111	54964.5	.015
4231	7/20/61	9.310	.0000285	.179	7.749	.105	46628.7	.019
4232	7/20/61	9.300	.0000285	.182	7.879	.114	47410.2	.020
4233	7/20/61	9.380	.0000289	.166	7.186	.100	42643.7	.021
4234	7/20/61	9.380	.0000289	.204	8.831	.150	52405.6	.021
4235	7/20/61	9.380	.0000289	.166	7.186	.090	42643.7	.019
4236	7/20/61	9.410	.0000290	.254	10.995	.200	65025.1	.018
4237	7/20/61	9.400	.0000290	.239	10.346	.175	61185.0	.018
4238	7/20/61	9.210	.0000284	.225	9.740	.194	58817.9	.023
4239	7/20/61	9.400	.0000290	.217	9.394	.182	55552.9	.023
4240	7/20/61	9.360	.0000289	.195	8.441	.132	50093.5	.020
4242	7/21/61	2.210	.0000094	.259	11.212	.118	204558.2	.010
4243	7/21/61	2.180	.0000094	.245	10.606	.111	193501.0	.011
4244	7/21/61	2.250	.0000094	.239	10.346	.109	188762.2	.011
4245	7/21/61	2.240	.0000092	.248	10.736	.148	200128.5	.014
4246	7/21/61	2.300	.0000092	.234	10.130	.106	188830.9	.011
4247	7/21/61	2.200	.0000092	.224	9.697	.102	180761.2	.012
4248	7/21/61	2.250	.0000092	.225	9.740	.135	181568.2	.016
4249	7/21/61	2.180	.0000092	.168	7.273	.076	135570.9	.016
4250	7/21/61	2.190	.0000092	.158	6.840	.072	127501.2	.017
4251	7/21/61	2.160	.0000092	.137	5.931	.062	110554.8	.019
4252	7/ 7/61	15.580	.0000455	.242	10.476	.241	39486.5	.024
4253	7/ 7/61	18.730	.0000548	.188	8.138	.090	25469.6	.015
4254	7/ 7/61	18.530	.0000547	.171	7.402	.063	23208.9	.013
4255	7/ 7/61	13.620	.0000393	.160	6.926	.116	30225.4	.027
4263	7/13/61	13.960	.0000417	.166	7.186	.189	29554.1	.040
4264	7/13/61	13.870	.0000420	.186	8.052	.203	32878.2	.035
4265	7/13/61	13.870	.0000420	.211	9.134	.160	37297.4	.021
4266	7/13/61	13.870	.0000414	.179	7.749	.137	32099.5	.025
4268	7/13/61	13.870	.0000414	.166	7.186	.058	29768.2	.012
4267	7/13/61	13.870	.0000414	.182	7.879	.089	32637.4	.016
4269	7/13/61	13.870	.0000414	.182	7.879	.089	32637.4	.016

TABLE F - 20

4700 SERIES - FINES-WATER SLURRY, FLUME 2% SLOPE

(a)

Run No	Date	Bed Type	Temp. °F.	Concentr'n. Fines, % by Volume	Apparent Kinematic Viscosity of Slurry, $Ft^2/Sec. \times 10^4$	Kinematic Viscosity of Water $\times 10^4$	Specific Gravity of Slurry from Sample	Specific Gravity from Weigh Tank	Discharge, $Ft^3/Sec.$
4714	7/13/61	2	84.0	12.42	3.73	.88	1.21	1.22	.230
4715	7/13/61	2	84.0	12.42	3.73	.88	1.21	1.21	.230
4717	7/13/61	2	85.0	12.42	3.72	.87	1.21	1.21	.234
4718	7/13/61	2	85.8	12.42	3.72	.87	1.21	1.20	.234
4719	7/13/61	2	85.0	12.42	3.72	.87	1.21	1.22	.229
4720	7/13/21	2	85.0	12.42	3.72	.87	1.21	1.23	.220
4721	7/13/61	2	85.0	12.42	3.72	.87	1.21	1.18	.216
4724	7/14/61	2	85.0	12.83	3.84	.87	1.22	1.20	.523
4740	7/14/61	2	84.0	13.05	3.92	.88	1.22	1.22	.234
4741	7/14/61	2	85.0	13.17	3.92	.87	1.23	1.25	.227
4742	7/20/61	2	86.0	13.07	3.87	.86	1.22	1.22	.227
4743	7/20/61	2	86.0	13.20	3.92	.86	1.23	0.00	.227
4749	7/20/61	2	80.0	9.34	2.95	.93	1.16	1.14	.219
4750	7/20/61	2	80.0	9.38	2.95	.93	1.16	1.16	.232
4751	7/20/61	2	81.0	5.87	1.91	.91	1.10	1.17	.205
4752	7/20/61	2	81.0	9.48	2.96	.91	1.16	1.15	.201
4753	7/20/61	2	82.0	9.42	2.95	.90	1.16	1.15	.188
4754	7/20/61	2	82.0	9.33	2.95	.90	1.16	1.15	.171
4755	7/20/61	2	82.0	9.26	2.90	.90	1.16	1.14	.160
4756	7/20/61	2	82.0	9.26	2.90	.90	1.16	1.15	.139
4758	7/20/61	2	83.0	9.25	2.85	.89	1.16	1.14	.108
4759	7/20/61	2	83.0	9.24	2.85	.89	1.16	1.17	.075
4760	7/20/61	2	83.0	9.04	2.80	.89	1.15	1.16	.039
4761	7/20/61	2	84.0	8.58	2.62	.88	1.15	1.15	.041
4762	7/20/61	2	84.0	9.34	2.89	.88	1.16	1.15	.129
4763	7/20/61	2	84.0	9.31	2.89	.88	1.16	1.16	.166
4764	7/20/61	2	84.0	9.37	2.87	.88	1.16	1.12	.186
4765	7/20/61	2	84.0	9.34	2.88	.88	1.16	1.17	.211
4766	7/20/61	2	84.0	9.34	2.87	.88	1.16	1.12	.179
4767	7/20/61	2	84.0	9.33	2.87	.88	1.16	1.14	.182
4768	7/20/61	2	84.0	9.41	2.88	.88	1.16	1.16	.166
4769	7/20/61	2	84.0	9.41	2.88	.88	1.16	1.17	.204
4770	7/20/61	2	84.0	9.41	2.88	.88	1.16	1.18	.166
4771	7/20/61	2	84.0	9.44	2.89	.88	1.16	1.14	.254
4772	7/20/61	2	84.0	9.43	2.89	.88	1.16	1.15	.239
4773	7/20/61	2	84.0	9.24	2.82	.88	1.16	1.17	.225
4774	7/20/61	2	84.0	9.43	2.89	.88	1.16	1.17	.217
4775	7/20/61	2	84.0	9.40	2.89	.88	1.16	1.15	.195
4777	7.21/61	2	81.0	2.22	1.01	.91	1.04	1.02	.259
4778	7/21/61	2	82.0	2.19	1.01	.90	1.04	1.04	.245
4779	7/21/61	2	82.0	2.26	1.01	.90	1.04	1.07	.239
4781	7/21/61	2	87.0	2.25	.91	.85	1.04	1.03	.248
4782	7/21/61	2	87.0	2.31	.91	.85	1.04	1.05	.234
4783	7/21/61	2	87.0	2.21	.91	.85	1.04	1.04	.224
4785	7/21/61	2	87.0	2.25	.91	.85	1.04	1.04	.225
4786	7/21/61	2	87.0	2.19	.91	.85	1.04	1.07	.168
4787	7/21/61	2	87.0	2.19	.91	.85	1.04	1.06	.158
4788	7/21/61	2	87.0	2.17	.91	.85	1.04	.98	.137

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(b)

Run Nº	Velocity, Ft./Sec.	Upstream Depth, Ft.	Downstream Depth, Ft.	Mean Depth, Ft.	Hydraulic Radius, Ft.	Breadth-to-Depth Ratio	Froude Number
4714	4.38	.106	.104	.105	.074	4.762	5.67
4715	4.53	.103	.101	.102	.072	4.918	6.27
4717	4.72	.099	.099	.099	.071	5.042	6.97
4718	4.76	.098	.098	.098	.071	5.085	7.15
4719	4.78	.096	.096	.096	.069	5.217	7.39
4720	4.77	.094	.091	.092	.068	5.405	7.63
4721	4.80	.091	.089	.090	.066	5.556	7.96
4724	5.73	.183	.182	.183	.105	2.740	5.59
4740	4.74	.098	.099	.099	.071	5.063	7.06
4741	4.76	.095	.096	.095	.069	5.240	7.36
4742	4.76	.095	.096	.095	.069	5.240	7.38
4743	4.95	.092	.091	.092	.067	5.455	8.29
4749	4.06	.113	.103	.108	.075	4.633	4.75
4750	4.53	.106	.099	.102	.073	4.878	6.22
4751	4.30	.097	.093	.095	.069	5.240	6.01
4752	4.42	.092	.089	.091	.067	5.505	6.69
4753	4.57	.085	.080	.082	.062	6.061	7.84
4754	4.22	.082	.079	.081	.061	6.186	6.85
4755	4.16	.078	.076	.077	.059	6.487	6.97
4756	4.15	.069	.065	.067	.053	7.453	7.98
4758	3.82	.058	.055	.057	.046	8.824	7.98
4759	3.18	.047	.047	.047	.040	1.062	6.67
4760	2.22	.036	.034	.035	.031	1.429	4.38
4761	2.53	.033	.032	.032	.029	1.539	6.13
4762	3.98	.067	.063	.065	.052	7.692	7.57
4763	4.42	.081	.069	.075	.058	6.667	8.09
4764	4.60	.085	.077	.081	.061	6.186	8.14
4765	4.49	.097	.092	.094	.068	5.310	6.64
4766	4.21	.088	.082	.085	.063	5.882	6.48
4767	4.23	.088	.083	.086	.064	5.825	6.47
4768	4.13	.082	.079	.080	.061	6.218	6.58
4769	4.52	.092	.088	.090	.066	5.530	7.02
4770	4.27	.081	.075	.078	.059	6.417	7.25
4771	4.85	.108	.101	.105	.074	4.781	6.98
4772	4.79	.103	.097	.100	.071	5.000	7.12
4773	4.70	.097	.094	.096	.069	5.217	7.17
4774	4.71	.093	.091	.092	.067	5.430	7.49
4775	4.72	.081	.084	.082	.062	6.061	8.40
4777	5.05	.105	.100	.102	.073	4.878	7.72
4778	4.88	.104	.097	.100	.072	4.979	7.37
4779	4.62	.108	.100	.104	.073	4.819	6.39
4781	4.91	.104	.097	.101	.072	4.959	7.43
4782	4.76	.101	.096	.098	.071	5.085	7.15
4783	4.81	.097	.089	.093	.068	5.357	7.68
4785	5.35	.088	.081	.084	.063	5.941	10.57
4786	4.22	.082	.077	.080	.060	6.283	6.93
4787	4.31	.076	.071	.073	.057	6.818	7.87
4788	4.28	.066	.062	.064	.051	7.792	8.85

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(c)

Run N°	Reynolds N° in Terms of Water Viscosity	Reynolds N° in Terms of Slurry Viscosity	Friction Factor	Manning's "n"	King's Constant in Terms of Water Viscosity	King's Constant in Terms of Slurry Viscosity	Shear Velocity, Ft./Sec.	Velocity Ratio
4714	147293.6	34750.2	.0199	.008	12.70	18.22	.22	.05
4715	148287.3	34984.7	.0181	.008	13.87	19.91	.22	.05
4717	153947.6	36003.9	.0164	.008	15.29	21.98	.21	.05
4718	155253.3	36309.2	.0162	.008	15.67	22.54	.21	.04
4719	151546.2	35442.3	.0156	.007	16.13	23.10	.21	.04
4720	149006.0	34848.2	.0154	.007	16.76	24.10	.21	.04
4721	145715.9	34078.7	.0147	.007	17.36	24.96	.21	.04
4724	276813.8	62715.6	.0165	.008	11.64	16.88	.26	.05
4740	152843.6	34311.8	.0163	.008	15.45	22.44	.21	.05
4741	150848.3	33479.1	.0157	.007	16.16	23.55	.21	.04
4742	152827.0	33961.6	.0157	.007	16.16	23.53	.21	.04
4743	154131.2	33814.5	.0141	.007	17.83	26.05	.21	.04
4749	131000.0	41298.3	.0234	.009	10.97	14.64	.22	.05
4750	142232.3	44839.3	.0183	.008	14.06	18.77	.22	.05
4751	130356.9	62107.2	.0192	.008	13.70	16.49	.21	.05
4752	130259.8	40046.1	.0176	.008	15.03	20.19	.21	.05
4753	125791.1	38376.9	.0153	.007	17.58	23.66	.20	.04
4754	114436.0	34912.7	.0176	.008	15.52	20.88	.20	.05
4755	109110.7	33861.9	.0176	.008	15.92	21.33	.19	.05
4756	97802.7	30352.6	.0158	.007	18.23	24.43	.18	.04
4758	78871.9	24630.2	.0163	.007	18.43	24.65	.17	.05
4759	57150.6	17847.0	.0204	.008	16.24	21.73	.16	.05
4760	30958.2	9840.3	.0323	.009	11.65	15.52	.14	.06
4761	33380.5	11214.8	.0233	.008	15.98	21.00	.14	.05
4762	94120.0	28659.4	.0169	.007	17.37	23.38	.18	.05
4763	116500.9	35474.3	.0153	.007	18.06	24.31	.19	.04
4764	127628.6	39133.5	.0148	.007	17.96	24.14	.20	.04
4765	138658.2	42367.8	.0174	.008	14.80	19.90	.21	.05
4766	120559.1	36965.9	.0183	.008	14.64	19.68	.20	.05
4767	123054.6	37731.0	.0184	.008	14.59	19.61	.20	.05
4768	114458.2	34973.3	.0184	.008	15.03	20.22	.20	.05
4769	135660.0	41451.7	.0166	.008	15.67	21.08	.21	.05
4770	114379.6	34949.3	.0167	.008	16.32	21.95	.19	.05
4771	163069.1	49654.3	.0162	.008	15.17	20.42	.22	.05
4772	154554.1	47061.5	.0159	.008	15.59	20.99	.21	.04
4773	147471.8	46019.6	.0161	.008	15.73	21.05	.21	.04
4774	143471.4	43686.8	.0156	.007	16.47	22.17	.21	.04
4775	133130.9	40538.1	.0143	.007	18.57	24.99	.20	.04
4777	161979.8	145942.2	.0148	.007	16.90	17.35	.22	.04
4778	156256.0	139238.0	.0156	.007	16.22	16.70	.22	.04
4779	149763.6	133452.7	.0177	.008	14.14	14.55	.22	.05
4781	166396.2	155425.1	.0154	.007	15.99	16.27	.22	.04
4782	158906.4	148429.0	.0162	.008	15.58	15.85	.21	.04
4783	153760.0	143622.0	.0151	.007	16.72	17.01	.21	.04
4785	158641.4	148181.5	.0113	.006	22.35	22.73	.20	.04
4786	199011.8	111164.8	.0174	.008	15.45	15.72	.20	.05
4787	115636.2	108011.9	.0158	.007	17.62	17.92	.19	.04
4788	102624.0	95857.6	.0144	.007	19.81	20.15	.18	.04

TABLE F-21

4900 SERIES - FINES-WATER SLURRY, FLUME 4% SLOPE

(a)

Run Nº	Date	Bed Type	Temp. °F.	Concentr'n. Fines, % by Volume	Apparent Kinematic Viscosity of Slurry, Ft.²/Sec. x 10^4	Kinematic Viscosity of Water x 10^4	Specific Gravity of Slurry from Sample	Specific Gravity from Weigh Tank	Discharge, Ft.³/Sec.
4992	7/ 7/61	2	89.0	18.79	5.43	.83	1.32	1.30	.060
4993	7/ 7/61	2	87.0	18.59	5.43	.85	1.32	1.27	.011
4994	7/10/61	2	92.0	13.67	3.91	.80	1.23	1.29	.191
4901	7/12/61	2	85.0	14.00	4.16	.87	1.24	1.24	.497
4915	7/12/61	2	85.0	14.00	4.16	.87	1.24	1.21	.505
4902	7/12/61	2	85.0	14.00	4.16	.87	1.24	1.22	.434
4916	7/12/61	2	85.0	14.00	4.16	.87	1.24	1.22	.405
4903	7/12/61	2	85.0	14.00	4.16	.87	1.24	1.23	.366
4904	7/12/61	2	85.0	14.00	4.16	.87	1.24	1.26	.291
4905	7/12/61	2	85.0	14.00	4.16	.97	1.24	1.23	.257
4906	7/13/61	2	85.0	14.00	4.16	.87	1.24	1.23	.218
4917	7/13/61	2	83.0	13.91	4.17	.88	1.24	1.87	.146
4907	7/13/61	2	83.0	13.91	4.17	.88	1.24	1.26	.187
4908	7/13/61	2	85.0	13.91	4.23	.87	1.24	1.19	.184
4909	7/13/61	2	85.0	13.91	4.23	.87	1.24	1.25	.154
4910	7/13/61	2	85.0	13.91	4.23	.87	1.24	1.25	.119
4911	7/13/61	2	85.0	13.91	4.23	.87	1.24	1.22	.056
4918	7/13/61	2	85.0	13.91	4.23	.87	1.24	1.24	.055

(F - 21)

(b)

Run Nº	Velocity, Ft./Sec.	Upstream Depth, Ft.	Downstream Depth, Ft.	Mean Depth, Ft.	Hydraulic Radius, Ft.	Breadth-to-Depth Ratio	Froude Number
4992	1.65	.064	.082	.073	.056	6.857	1.16
4993	.30	.078	.076	.077	.059	6.487	.04
4994	5.25	.077	.069	.073	.056	6.857	11.72
4901	7.08	.142	.138	.140	.090	3.561	11.08
4915	7.19	.142	.138	.140	.090	3.561	11.43
4902	6.70	.136	.123	.130	.085	3.859	10.74
4916	6.24	.136	.123	.130	.085	3.859	9.34
4903	6.35	.121	.110	.115	.079	4.332	10.84
4904	5.95	.103	.093	.098	.070	5.106	11.22
4905	6.00	.091	.081	.086	.064	5.825	13.02
4906	5.65	.082	.072	.077	.059	6.487	12.88
4917	3.80	.082	.072	.077	.059	6.487	5.81
4907	5.33	.074	.066	.070	.055	7.143	12.61
4908	5.58	.070	.062	.066	.052	7.595	14.70
4909	5.01	.066	.057	.062	.049	8.108	12.64
4910	4.11	.062	.054	.058	.047	8.633	9.06
4911	4.73	.030	.017	.024	.022	2.105	29.29
4918	4.61	.030	.017	.024	.022	2.105	27.82

(F - 21)

(c)

Run Nº	Reynolds Nº in Terms of Water Viscosity	Reynolds Nº in Terms of Slurry Viscosity	Friction Factor	Manning's "n"	King's Constant in Terms of Water Viscosity	King's Constant in Terms of Slurry Viscosity	Shear Velocity, Ft./Sec.	Velocity Ratio
4992	44530.1	6806.6	.1060	.027	3.26	5.22	.19	.12
4993	8246.1	1290.8	3.4460	.152	.15	.25	.19	.66
4994	146860.0	30048.1	.0105	.008	14.46	36.36	.19	.04
4901	292882.8	61251.9	.0093	.008	22.00	32.54	.24	.03
4915	297434.5	62203.8	.0090	.008	22.60	33.43	.24	.03
4902	261682.8	54726.9	.0098	.009	21.50	31.80	.23	.03
4916	243979.3	51024.5	.0112	.009	19.02	28.13	.23	.04
4903	230534.7	48212.8	.0101	.009	22.13	32.73	.23	.04
4904	191365.5	40021.2	.0102	.009	23.17	34.26	.21	.04
4905	176492.9	36910.8	.0092	.008	26.81	39.64	.20	.03
4906	153372.9	32075.6	.0095	.008	27.00	39.93	.19	.03
4917	101828.6	21489.0	.0211	.012	13.49	19.90	.19	.05
4907	133275.0	28125.2	.0100	.008	26.87	39.65	.19	.04
4908	133454.7	27448.1	.0086	.007	30.80	45.74	.18	.03
4909	112869.0	23214.2	.0101	.008	27.14	40.30	.18	.04
4910	88835.4	18271.1	.0143	.009	20.52	30.47	.17	.04
4911	47874.0	9846.4	.0051	.005	63.46	94.24	.12	.03
4918	46660.2	9596.8	.0053	.005	60.68	90.10	.12	.03

TABLE F-22

5400 SERIES - FINES-SAND-WATER SLURRY, 2" STEEL PIPELINE

Run Nº	Date	Concentr'n. of Fines, % by Vol.	Concentr'n. of Sand, % by Vol.	Apparent Kinematic Viscosity Fines-Water Slurry, $Ft.^2/Sec.$	Discharge $Ft.^3/Sec.$	Velocity, Ft./Sec.	Hydraulic Gradient, Ft. Water per Ft.	Reynolds Nº in Terms of Fines-Water Slurry Viscosity	Friction Factor	Kinematic Viscosity of Water at Oper. Temp.
5497	12/31/61	8.130	8.090	.0000260	.243	10.519	.225	69387.0	.022	.000009[illegible]
5490	12/22/61	7.480	7.730	.0000224	.243	10.519	.208	80538.4	.021	.0000087
5489	12/22/61	7.720	2.600	.0000242	.097	4.199	.040	29757.8	.025	.0000091
5488	12/22/61	7.430	7.390	.0000238	.173	7.489	.120	53365.2	.024	.0000091
5470	12/11/61	8.660	7.500	.0000272	.186	8.052	.143	50767.9	.024	.0000091
5471	12/13/61	9.520	7.800	.0000303	.244	10.563	.234	59785.0	.023	.0000095
5473	12/15/61	8.900	8.780	.0000275	.227	9.827	.211	61282.7	.024	.0000090
5476	12/19/61	8.040	7.860	.0000277	.242	10.476	.240	64860.5	.024	.0000106
5480	12/20/61	8.130	7.740	.0000270	.237	10.260	.249	65167.3	.026	.0000100
5481	12/20/61	8.130	7.570	.0000266	.225	9.740	.220	62798.0	.026	.0000095
5482	12/20/61	8.100	7.900	.0000264	.208	9.004	.177	58493.1	.024	.0000093
5483	12/20/61	8.360	6.130	.0000268	.174	7.532	.140	48201.4	.027	.000009[illegible]
5484	12/20/61	8.220	7.870	.0000260	.231	10.000	.208	65960.5	.023	.0000090
5485	12/20/61	8.140	7.300	.0000258	.199	8.615	.163	57263.6	.024	.0000091
5486	12/20/61	8.500	5.930	.0000270	.187	8.095	.137	51418.9	.023	.000009[illegible]
5413	10/ 2/61	8.930	12.200	.0000376	.230	9.957	.258	45113.5	.029	.0000097
5415	10/ 4/61	13.030	5.560	.0000389	.206	8.918	.240	39315.4	.033	.0000087
5425	10/23/61	10.160	8.900	.0000349	.248	10.736	.236	52755.9	.023	.0000106
5435	10/30/61	7.540	9.560	.0000245	.176	7.619	.117	53332.5	.022	.0000094
5437	10/31/61	8.240	8.100	.0000265	.132	5.714	.079	36980.5	.027	.0000095
5441	11/ 2/61	7.960	7.810	.0000266	.154	6.667	.10[illegible]	42981.7	.025	.0000100
5448	11/ 7/61	6.520	5.830	.0000218	.114	4.935	.058	38823.4	.026	.0000097
5401	9/25/61	16.230	5.750	.0000514	.084	3.636	.035	12132.8	.029	.0000106
5402	9/25/61	7.080	4.590	.0000250	.078	3.377	.029	23163.3	.028	.0000106
5406	9/27/61	9.350	9.010	.0000314	.126	5.541	.083	30263.9	.030	.0000104
5407	9/27/61	10.470	7.730	.0000345	.114	4.935	.061	24531.9	.028	.0000102
5409	9/28/61	9.200	8.230	.0000310	.133	5.757	.081	31851.9	.027	.0000104
5412	9.30/61	15.910	5.560	.0000500	.250	10.822	.268	37120.6	.025	.0000102
5414	10/ 2/61	11.730	9.420	.0000366	.221	9.567	.231	44828.7	.028	.0000095
5418	10/ 9/61	9.900	9.800	.0000330	.234	10.130	.295	52643.8	.032	.0000104
5419	10/ 9/61	10.160	9.170	.0000336	.234	10.130	.295	51703.7	.032	.0000104
5434	10/30/61	7.670	10.070	.0000247	.231	10.000	.212	69432.1	.023	.0000094
5444	11/ 3/61	6.510	9.000	.0000214	.235	10.173	.206	81526.5	.022	.0000095
5405	9/26/61	9.640	9.240	.0000321	.136	5.887	.085	31454.2	.027	.0000104
5410	9/28/61	9.370	8.550	.0000313	.112	4.848	.061	26565.5	.029	.0000104
5424	10/11/61	10.420	9.360	.0000331	.194	8.398	.159	43513.0	.025	.0000097
5431	10/25/61	8.770	.160	.0000293	.239	10.346	.232	60558.5	.024	.0000102
5439	11/ 1/61	7.670	10.100	.0000260	.150	6.493	.110	42831.5	.029	.0000100
5443	11/ 3/61	7.140	10.890	.0000233	.229	9.913	.210	72966.7	.024	.0000095
5449	11/ 7/61	6.440	8.590	.0000208	.183	7.922	.131	65318.0	.023	.0000091
5423	11/ 1/61	10.230	10.320	.0000331	.237	10.260	.242	53157.6	.025	.0000100
5428	10/24/61	8.020	9.690	.0000261	.228	9.870	.195	64854.4	.022	.0000094
5429	10/24/61	8.020	9.690	.0000258	.238	10.303	.195	64486.1	.020	.0000094
5430	10/24/61	8.080	9.960	.0000261	.217	9.394	.161	61725.4	.020	.0000095
5438	10/ 1/61	7.270	10.990	.0000251	.236	10.216	.212	69804.5	.022	.0000102
5442	10/ 2/61	7.820	10.940	.0000250	.231	10.000	.208	68598.9	.023	.0000093
5447	10/ 6/61	6.300	8.690	.0000213	.203	8.788	.112	70755.7	.016	.0000097
5496	12/31/61	8.130	8.060	.0000260	.235	10.173	.219	67102.6	.023	.0000092
5492	12/31/61	8.130	7.650	.0000259	.243	10.519	.227	69654.9	.023	.0000092
5493	12/31/61	8.120	7.400	.0000259	.245	10.606	.229	70228.2	.022	.0000092
5494	12/31/61	8.100	8.490	.0000292	.235	10.173	.231	59748.9	.025	.0000092
5498	12/31/61	8.140	8.470	.0000259	.243	10.519	.228	69654.9	.023	.0000092
5499	12/31/61	8.240	7.620	.0000260	.243	10.519	.220	69387.0	.022	.0000092

TABLE F - 23

5700 SERIES - FINES-SAND-WATER SLURRY, FLUME 2% SLOPE

(a - 1)

Run No	Date	Bed Type	Temp. °F.	Concentr'n. Fines, % by Volume	Concentr'n. Sand, % by Volume	Apparent Kinematic Viscosity of Slurry Ft²/Sec. x 10⁴	Kinematic Viscosity of Water, x 10⁴	Specific Gravity of Slurry from Sample	Specific Gravity from Weigh Tank
5756	11/24/61	1	80.0	6.48	7.11	2.13	.92	1.23	1.21
5731	10/25/61	4	73.0	8.77	.16	2.93	1.02	1.15	1.26
5725	10/23/61	1	70.0	10.16	8.90	3.49	1.05	1.32	1.33
5735	10/23/61	1	79.0	7.54	9.56	2.45	.94	1.29	1.23
5737	10/31/61	1	78.0	8.24	8.10	2.65	.95	1.27	1.26
5741	11/ 2/61	1	74.0	7.96	7.81	2.66	1.00	1.27	1.22
5748	11/ 7/61	1	76.0	6.52	5.83	2.18	.97	1.21	1.22
5700	9/25/61	2	69.5	7.21	8.83	2.58	1.06	1.27	1.25
5701	9/25/61	2	70.0	16.23	5.75	5.14	1.05	1.37	1.17
5702	9/25/61	2	70.0	7.08	4.59	2.50	1.05	1.20	1.18
5706	9/27/61	2	70.5	9.35	9.01	3.14	1.04	1.31	1.31
5707	9/27/61	2	72.0	10.47	7.73	3.45	1.03	1.31	1.26
5709	9/28/61	2	70.5	9.20	8.23	3.10	1.04	1.29	1.27
5713	10/ 2/61	2	76.0	11.95	9.15	3.76	.97	1.36	1.26
5714	10/ 2/61	2	78.0	11.73	9.42	3.66	.95	1.36	1.32
5718	10/ 9/61	2	71.0	9.90	9.80	3.30	1.04	1.33	1.31
5719	10/ 9/61	2	71.0	10.16	9.17	3.36	1.04	1.33	1.33
5722	10/ 9/61	2	78.0	10.07	10.18	3.16	.95	1.34	1.41
5734	10/30/61	2	79.0	7.67	10.07	2.47	.94	1.30	1.30
5705	9/26/61	3	71.0	9.64	9.24	3.21	1.04	1.32	1.28
5710	9/28/61	3	71.0	9.37	8.55	3.13	1.04	1.30	1.24
5736	10/31/61	3	74.0	7.60	11.48	2.58	1.00	1.32	1.29
5739	11/ 1/61	3	74.0	7.67	10.10	2.60	1.00	1.30	1.25
5743	11/ 3/61	3	78.0	7.14	10.89	2.33	.95	1.30	1.27
5749	11/ 7/61	3	81.0	6.44	8.59	2.08	.92	1.25	1.25
5711	10/11/61	0	74.0	10.13	10.45	3.30	1.00	1.35	1.33
5723	10/11/61	4	74.0	10.23	10.32	3.31	1.00	1.35	1.29
5728	10/24/61	4	79.0	8.35	6.80	2.61	.94	1.28	1.29
5729	10/24/61	4	79.0	8.02	9.69	2.58	.94	1.30	1.24
5730	10/24/61	4	78.0	8.08	9.96	2.61	.95	1.30	1.28
5738	11/ 1/61	4	72.0	7.27	10.99	2.51	1.02	1.31	1.25
5742	11/ 2/61	4	80.0	7.82	10.94	2.50	.93	1.31	1.28
5747	11/ 6/61	4	76.0	6.30	8.69	2.13	.97	1.25	1.18
5746	11/ 6/61	4	71.0	6.52	6.89	2.32	1.04	1.23	1.20
5727	10/24/61	4	77.0	7.93	9.72	2.56	.97	1.30	1.22
5726	10/24/61	4	77.0	7.89	9.93	2.55	.97	1.30	1.30
5744	11/ 3/61	2	78.0	6.51	9.00	2.14	.95	1.26	1.23
5712	9/ 3/61	2	72.0	15.91	10.17	5.00	1.03	1.44	1.30
5715	10/ 4/61	1	85.0	13.03	5.56	3.89	.87	1.31	1.28
5740	11/ 1/61	2	74.0	7.61	9.72	2.60	1.00	1.29	1.26
5724	10/ 1/61	3	76.0	10.42	9.36	3.31	.97	1.33	1.26
5767	12/ 8/61	1	73.0	7.78	6.63	2.68	1.02	1.24	1.18
5766	12/ 7/61	1	83.0	8.27	6.19	2.55	.89	1.24	1.19
5765	12/ 7/61	4	81.0	7.97	8.15	2.51	.91	1.27	1.24

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(a - 2)

Run Nº	Date	* Bed Type	Temp. °F.	Concentr'n. Fines, % by Volume	Concentr'n. Sand, % by Volume	Apparent Kinematic Viscosity of Slurry Ft²/Sec. x 10⁴	Kinematic Viscosity of Water, x 10⁴	Specific Gravity of Slurry from Sample	Specific Gravity from Weigh Tank
5764	12/ 7/61	4	73.0	8.20	8.30	2.67	.95	1.28	1.25
5763	12/ 6/61	4	80.0	7.94	7.66	2.53	.92	1.26	1.26
5761	12/ 1/61	4	73.0	6.52	8.90	2.16	.95	1.26	1.21
5760	12/ 1/61	3	72.0	6.52	8.79	2.33	1.02	1.26	1.19
5750	11/20/61	2	70.0	6.08	6.00	2.23	1.06	1.20	1.15
5751	11/21/61	2	78.0	6.03	7.54	2.01	.95	1.23	1.14
5752	11/22/61	2	74.0	6.50	7.79	2.28	1.00	1.24	1.24
5753	11/22/61	1	80.0	6.20	7.68	2.04	.92	1.23	1.21
5754	11/23/61	2	70.0	6.01	8.88	2.22	1.06	1.25	1.19
5757	11/27/61	4	72.0	6.12	9.34	2.21	1.01	1.26	1.21
5758	11/27/61	1	78.0	6.45	5.80	2.12	.95	1.21	1.13
5759	11/30/61	1	71.0	6.64	2.64	2.37	1.04	1.16	1.17
5793	12/31/61	4	80.0	8.12	7.40	3.95	.92	1.26	1.26
5796	12/31/61	3	80.0	8.13	8.06	2.60	.92	1.27	1.25
5799	12/31/61	3	80.0	8.24	7.62	2.60	.92	1.27	1.23
5792	12/31/61	4	80.0	8.13	7.65	2.56	.92	1.27	1/25
5798	12/31/61	4	80.0	3.14	8.47	2.56	.92	1.28	1.22
5791	12/31/61	4	80.0	8.12	7.00	2.56	.92	1.25	1.25
5797	12/31/61	4	80.0	8.13	8.09	2.56	.92	1.27	1.24
5790	12/22/61	4	85.0	7.48	7.73	2.22	.88	1.26	1.21
5789	12/22/61	1	81.0	7.72	2.60	2.41	.91	1.17	1.14
5788	12/22/61	4	81.0	7.43	7.39	2.32	.91	1.25	1.19
5794	12/31/61	4	80.0	8.10	8.49	2.78	.92	1.28	1.31
5768	12/ 8/61	3	83.0	8.17	9.48	2.50	.89	1.30	1.25
5760	12/11/61	4	78.0	8.59	7.82	2.72	.95	1.28	1.24
5770	12/11/61	1	81.0	8.66	7.50	2.72	.91	1.27	1.22
5771	12/13/61	4	78.0	9.52	7.80	3.03	.95	1.29	1.28
5772	12/13/61	1	81.0	8.77	7.13	2.75	.91	1.27	1.24
5773	12/15/61	3	82.0	8.90	8.78	2.75	.90	1.30	1.29
5774	12/15/61	3	78.0	9.11	8.26	2.89	.95	1.29	1.25
5776	12/19/61	4	70.0	8.04	7.86	2.77	1.06	1.27	1.27
5777	12/19/61	4	74.0	7.97	7.33	2.70	1.00	1.26	1.31
5778	12/19/61	4	76.0	8.02	7.50	2.68	.98	1.26	1.20
5780	12/20/61	4	74.0	8.13	7.74	2.70	1.00	1.27	1.25
5781	12/20/61	4	78.0	8.13	7.57	2.66	.95	1.26	0.00
5782	12/20/61	3	79.0	8.10	7.90	2.64	.93	1.27	1.22
5783	12/20/61	1	80.0	8.36	6.13	2.68	.92	1.24	1.27
5784	12/20/61	4	82.0	8.22	7.87	2.60	.90	1.27	1.27
5785	12/20/61	3	81.0	8.14	7.30	2.58	.91	1.26	1.24
5786	12/20/61	1	80.0	8.50	5.93	2.70	.92	1.24	1.22

(Continued ...)

(F-23) - Continued

(b - 1)

Run Nº	Discharge, Ft³/Sec.	Velocity, Ft./Sec.	Upstream Depth, Ft.	Downstream Depth, Ft.	Mean Depth, Ft.	Hydraulic Radius, Ft.	Breadth-to-Depth Ratio	Froude Number
5756	.118	3.34	.069	.072	.071	.055	7.059	4.86
5731	.239	4.48	.108	.106	.107	.075	4.673	5.84
5725	.248	4.20	.114	.122	.118	.080	4.240	4.65
5735	.176	4.11	.086	.086	.086	.064	5.825	6.10
5737	.132	3.61	.074	.072	.073	.057	6.818	5.53
5741	.154	3.89	.079	.079	.079	.060	6.316	5.93
5748	.114	3.41	.068	.066	.067	.053	7.500	5.41
5700	.132	3.36	.080	.077	.079	.060	6.349	4.46
5701	.084	2.97	.057	.055	.056	.046	8.889	4.88
5702	.078	3.00	.053	.051	.052	.043	9.600	5.37
5706	.128	3.37	.076	.076	.076	.058	6.593	4.66
5707	.114	2.88	.078	.079	.079	.060	6.349	3.28
5709	.133	3.45	.078	.076	.077	.059	6.497	4.80
5713	.230	3.11	.147	.148	.147	.093	3.390	2.01
5714	.221	3.32	.141	.126	.133	.087	3.750	2.56
5718	.234	4.28	.112	.107	.109	.076	4.580	5.22
5719	.234	4.28	.112	.107	.109	.076	4.580	5.22
5722	.203	3.60	.116	.109	.113	.078	4.444	3.58
5734	.231	4.36	.106	.106	.106	.074	4.724	5.58
5705	.136	3.62	.079	.071	.075	.058	6.667	5.47
5710	.112	3.12	.068	.076	.072	.056	6.936	4.11
5736	.222	4.21	.108	.103	.105	.074	4.743	5.22
5739	.150	3.37	.088	.091	.089	.066	5.608	3.97
5743	.229	4.30	.112	.102	.107	.075	4.688	5.39
5749	.183	4.12	.089	.088	.089	.065	5.634	5.95
5711	.234	4.07	.116	.114	.115	.079	4.348	4.47
5723	.237	4.12	.116	.114	.115	.079	4.348	4.59
5728	.228	4.38	.108	.101	.104	.074	4.800	5.71
5729	.238	4.57	.108	.101	.104	.074	4.800	6.23
5730	.217	4.57	.097	.093	.095	.069	5.263	6.82
5738	.236	4.45	.109	.103	.106	.075	4.706	5.78
5742	.231	4.36	.108	.104	.106	.074	4.724	5.57
5747	.203	4.46	.093	.088	.091	.067	5.505	6.80
5746	.243	4.46	.111	.107	.109	.076	4.580	5.66
5727	.249	4.52	.114	.107	.110	.077	4.528	5.74
5726	.243	4.41	.114	.107	.110	.077	4.528	5.46
5744	.235	4.48	.107	.103	.105	.074	4.762	5.94
5712	.250	4.42	.118	.109	.113	.078	4.412	5.34
5715	.206	2.14	.192	.192	.192	.109	2.597	.74
5740	.154	3.80	.083	.079	.081	.061	6.154	5.52
5724	.194	3.61	.108	.107	.108	.075	4.651	3.77
5767	.138	3.56	.077	.077	.077	.059	6.452	5.07
5766	.162	3.70	.088	.088	.088	.065	5.687	4.83
5765	.194	3.82	.102	.102	.102	.072	4.918	4.46

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(b - 2)

Run Nº	Discharge, Ft³/Sec.	Velocity, Ft./Sec.	Upstream Depth, Ft.	Downstream Depth, Ft.	Mean Depth, Ft.	Hydraulic Radius, Ft.	Breadth-to-Depth Ratio	Froude Number
5764	.249	4.42	.114	.111	.113	.078	4.444	5.40
5763	.245	4.27	.114	.115	.115	.079	4.364	4.94
5761	.146	3.31	.089	.087	.088	.065	5.687	3.87
5760	.170	3.48	.106	.089	.097	.070	5.128	3.85
5750	.246	4.37	.113	.112	.112	.078	4.444	5.27
5751	.175	4.05	.088	.085	.087	.064	5.769	5.87
5752	.244	4.34	.113	.113	.113	.078	4.444	5.20
5753	.108	3.23	.067	.067	.067	.053	7.453	4.82
5754	.147	3.61	.083	.079	.081	.061	6.154	4.99
5757	.231	4.22	.110	.109	.110	.076	4.563	5.06
5758	.125	3.61	.000	.069	.069	.054	7.229	5.84
5759	.065	2.14	.061	.000	.061	.049	8.219	2.33
5793	.245	3.84	.121	.134	.127	.084	3.922	3.59
5796	.235	3.84	.119	.126	.123	.082	4.082	3.75
5799	.243	3.98	.119	.126	.123	.082	4.082	4.01
5792	.243	3.80	.123	.132	.128	.085	3.909	3.50
5798	.243	3.98	.119	.126	.123	.082	4.082	4.01
5791	.243	3.81	.121	.134	.127	.084	3.922	3.53
5797	.243	3.98	.119	.126	.123	.082	4.082	4.01
5790	.243	4.46	.109	.109	.109	.076	4.580	5.65
5789	.097	1.85	.124	.085	.105	.074	4.781	1.02
5788	.173	3.67	.101	.088	.095	.069	5.286	4.42
5794	.235	3.69	.121	.134	.127	.084	3.922	3.32
5768	.246	4.31	.116	.113	.114	.078	4.380	5.05
5769	.247	4.20	.118	.000	.118	.080	4.255	4.66
5770	.186	3.67	.099	.103	.101	.072	4.938	4.13
5771	.244	3.95	.221	.026	.123	.083	4.054	3.93
5772	.203	3.60	.110	.116	.113	.078	4.428	3.57
5773	.227	3.31	.136	.138	.137	.089	3.647	2.49
5774	.234	3.50	.136	.132	.134	.087	3.738	2.84
5776	.242	4.16	.118	.114	.116	.079	4.301	4.62
5777	.196	3.70	.108	.104	.106	.074	4.724	4.02
5778	.191	3.83	.101	.098	.100	.071	5.021	4.58
5780	.237	4.04	.118	.117	.118	.080	4.255	4.30
5781	.225	4.16	.110	.106	.108	.075	4.633	4.98
5782	.208	3.82	.109	.108	.109	.076	4.598	4.17
5783	.174	3.44	.104	.098	.101	.072	4.938	3.62
5784	.231	3.85	.119	.121	.120	.081	4.167	3.83
5785	.199	3.45	.117	.114	.115	.079	4.332	3.22
5786	.187	3.61	.104	.103	.104	.073	4.819	3.89

(Continued ...)

(c- 1)

Run Nº	Reynolds Nº in Terms of Water Viscosity	Reynolds Nº in Terms of Slurry Viscosity	Friction Factor	Manning's "n"	King's Constant in Terms of Water Viscosity	King's Constant in Terms of Slurry Viscosity	Shear Velocity, Ft./Sec.	Velocity Ratio
5756	79773.9	34456.3	.0255	.009	11.80	14.55	.19	.06
5731	131764.7	45870.3	.0193	.008	13.45	17.52	.22	.05
5725	128000.0	38510.0	.0234	.009	10.98	14.82	.23	.05
5735	111795.7	42893.1	.0196	.008	14.08	17.88	.20	.05
5737	86688.0	31076.8	.0225	.009	13.29	17.18	.19	.05
5741	93336.0	35088.7	.0204	.008	14.16	18.08	.20	.05
5748	74440.4	33122.6	.0235	.009	13.13	16.08	.18	.05
5700	76120.8	31274.4	.0273	.010	11.13	13.91	.20	.06
5701	52098.3	10642.6	.0268	.009	12.63	18.79	.17	.06
5702	49159.2	20646.9	.0246	.009	13.83	17.18	.17	.06
5706	75243.8	24921.5	.0263	.009	11.58	15.27	.19	.06
5707	67176.7	20055.7	.0372	.011	8.45	11.43	.20	.07
5709	78356.5	26287.4	.0255	.009	11.91	15.65	.19	.06
5713	119385.2	30798.8	.0494	.014	5.11	7.18	.24	.08
5714	121470.3	31529.2	.0408	.012	6.28	8.80	.24	.07
5718	125224.6	39464.7	.0213	.009	12.27	16.38	.22	.05
5719	125224.6	38760.0	.0213	.009	12.27	16.45	.22	.05
5722	118330.1	35573.9	.0310	.011	8.55	11.54	.22	.06
5734	137262.1	52237.4	.0201	.009	12.68	16.15	.22	.05
5705	80686.9	26141.6	.0228	.009	13.26	17.53	.19	.05
5710	67156.9	22314.1	.0197	.010	10.66	14.03	.19	.06
5736	124586.4	48289.3	.0215	.009	12.23	15.50	.22	.05
5739	89073.6	34259.1	.0299	.010	9.80	12.44	.21	.06
5743	135852.6	55390.6	.0209	.009	12.31	15.41	.22	.05
5749	116547.8	51550.0	.0197	.008	13.64	16.72	.20	.05
5711	128517.2	38944.6	.0246	.009	10.52	14.18	.23	.06
5723	130318.4	39371.1	.0239	.009	10.78	14.54	.23	.05
5728	137766.0	49616.9	.0199	.008	13.01	16.80	.22	.05
5729	143969.4	52454.0	.0182	.008	14.05	18.09	.22	.05
5730	132654.3	48284.1	.0171	.008	15.39	19.82	.21	.05
5738	130794.1	53151.4	.0195	.008	13.41	16.79	.22	.05
5742	138674.4	51586.9	.0201	.009	12.64	16.19	.22	.05
5747	123224.7	56116.4	.0174	.008	15.50	18.87	.21	.05
5746	130369.2	58441.4	.0197	.008	13.17	16.09	.22	.05
5727	143458.1	54357.2	.0194	.008	13.12	16.72	.22	.05
5726	139870.1	53205.5	.0204	.009	12.55	15.98	.22	.05
5744	139680.8	62007.9	.0190	.008	13.49	16.52	.22	.05
5712	133735.9	27549.6	.0206	.009	12.45	18.48	.22	.05
5715	107396.3	24019.2	.1223	.022	1.98	2.88	.26	.12
5740	92695.6	35652.2	.0218	.009	13.25	16.83	.20	.05
5724	111773.2	32755.3	.0296.	.010	9.04	12.29	.22	.06
5767	82299.2	31322.8	.0240	.009	12.49	15.90	.19	.05
5766	107973.0	37684.7	.0245	.009	11.29	14.69	.20	.06
5765	120865.1	43819.6	.0254	.010	10.37	13.37	.22	.06

...... Cont'd.

(c - 2)

Run Nº	Reynolds Nº in Terms of Water Viscosity	Reynolds Nº in Terms of Slurry Viscosity	Friction Factor	Manning's "n"	King's Constant in Terms of Water Viscosity	King's Constant in Terms of Slurry Viscosity	Shear Velocity, Ft./Sec.	Velocity Ratio
5764	145260.6	51684.5	.0205	.009	12.24	15.85	.22	.05
5763	146665.2	53332.8	.0223	.009	11.22	14.44	.23	.05
5761	90589.5	39842.6	.0306	.010	9.46	11.62	.20	.06
5760	95502.0	41807.7	.0298	.010	9.53	11.72	.21	.06
5750	128655.9	61154.8	.0210	.009	12.43	14.97	.22	.05
5751	109056.0	51543.9	.0201	.008	13.61	16.41	.20	.05
5752	135345.6	59362.1	.0214	.009	11.98	14.72	.22	.05
5753	74384.3	33545.9	.0262	.009	11.80	14.40	.18	.06
5754	83144.2	39699.5	.0241	.009	12.31	14.81	.20	.05
5757	127138.2	58103.9	.0219	.009	11.78	14.32	.22	.05
5758	81989.1	36740.4	.0214	.008	14.02	17.14	.19	.05
5759	40255.4	17664.8	.0553	.013	6.49	7.97	.18	.08
5793	140280.0	32672.8	.0293	.011	8.44	12.15	.23	.06
5796	137011.3	48480.9	.0286	.010	8.72	11.31	.23	.06
5799	141717.4	50146.2	.0267	.010	9.25	12.00	.23	.06
5792	140250.0	50402.0	.0304	.011	8.20	10.59	.23	.06
5798	141717.4	50929.7	.0267	.010	9.25	11.95	.23	.06
5791	139074.8	49980.0	.0298	.011	8.31	10.74	.23	.06
5797	141717.4	50929.7	.0267	.010	9.25	11.95	.23	.06
5790	153934.6	61019.1	.0197	.008	12.61	15.89	.22	.05
5789	60208.4	22734.3	.1113	.020	2.84	3.62	.22	.12
5788	111249.2	43636.6	.0264	.010	10.38	13.12	.21	.06
5794	134874.8	44634.8	.0317	.011	7.88	10.39	.23	.06
5768	151022.0	53763.8	.0217	.009	11.40	14.75	.22	.05
5769	141406.3	49388.2	.0234	.009	10.70	13.91	.23	.05
5770	116149.5	39858.8	.0275	.010	9.77	12.85	.22	.06
5771	138112.0	43302.4	.0274	.010	9.23	12.34	.23	.06
5772	123497.1	40866.3	.0310	.011	8.45	11.14	.22	.06
5773	131087.1	42901.2	.0418	.013	6.01	7.95	.24	.07
5774	128100.6	42109.2	.0367	.012	6.84	9.04	.24	.07
5776	124015.1	47457.0	.0235	.009	11.01	13.99	.23	.05
5777	109608.8	40595.9	.0278	.010	9.68	12.41	.22	.06
5778	111107.8	40629.0	.0249	.009	10.85	13.96	.21	.06
5780	129120.0	47822.2	.0253	.010	10.11	12.96	.23	.06
5781	131400.0	46928.6	.0223	.009	11.51	14.89	.22	.05
5782	124966.9	44022.4	.0268	.010	9.78	12.69	.22	.06
5783	107530.4	36913.4	.0314	.011	8.73	11.40	.22	.06
5784	138456.0	47927.1	.0282	.010	8.90	11.61	.23	.06
5785	119836.9	42268.1	.0342	.011	7.71	10.00	.23	.07
5786	114451.3	38998.2	.0289	.010	9.23	12.08	.22	.06

TABLE F - 24

RHEOLOGICAL DATA

SERIES 32,000 - FINES-WATER SLURRIES

Run Number	Date	Temperature, °F.	Concentration Fines, % by Volume	Coefficient of Rigidity Lb. Sec./Ft.^{2}	Yield Stress Lb./Ft.^{2}	Specific Gravity	Apparent Kinematic Viscosity
32001	8/21/61	77.0	.75	.000023	.009	1.01	.000012
32101	8/21/61	77.0	.75	.000023	.009	1.01	.000012
32008	9/ 8/61	86.0	1.07	.000023	-.006	1.02	.000012
32108	9/ 8/61	104.0	1.07	.000017	.009	1.02	.000008
32208	9/ 8/61	122.0	1.07	.000015	.008	1.02	.000008
32308	9/ 8/61	145.4	1.07	.000012	.009	1.02	.000006
32002	8/21/61	77.0	1.51	.000026	.011	1.03	.000013
32102	8/21/61	77.0	1.51	.000026	.011	1.03	.000013
32209	9/ 8/61	122.0	1.96	.000017	.013	1.03	.000008
32309	9/ 8/61	145.4	1.96	.000015	.010	1.03	.000007
32409	9/ 8/61	77.0	2.00	.000025	.010	1.03	.000013
32009	9/ 8/61	86.0	2.00	.000023	.009	1.03	.000012
32109	9/ 8/61	104.0	2.00	.000019	.011	1.03	.000010
32410	9/ 9/61	77.0	2.15	.000028	.007	1.04	.000014
32010	9/ 9/61	86.0	2.15	.000024	.010	1.04	.000012
32110	9/ 9/61	104.0	2.15	.000020	.011	1.04	.000010
32004	8/21/61	77.0	2.30	-.000007	.058	1.04	-.000003
32104	8/21/61	77.0	2.30	.000031	.018	1.04	.000016
32210	9/ 9/61	122.0	2.33	.000018	.010	1.04	.000009
32310	9/ 9/61	145.4	2.33	.000015	.015	1.04	.000007
32311	9/ 9/61	122.0	2.99	.000019	.011	1.05	.000009
32411	9/ 9/61	145.4	2.99	.000016	.016	1.05	.000008
32011	9/ 9/61	77.0	3.03	.000029	.013	1.05	.000014
32111	9/ 9/61	86.0	3.03	.000026	.010	1.05	.000013
32211	9/ 9/61	104.0	3.03	.000022	.014	1.05	.000011
32003	8/21/61	77.0	3.11	.000028	.016	1.05	.000014

TABLE F-25

RHEOLOGICAL DATA

SERIES 41,000 - FINES-WATER SLURRIES

Run Number	Date	Temperature, °F.	Concentration Fines, % by Volume	Coefficient of Rigidity Lb. Sec./Ft.²	Yield Stress Lb./Ft.²	Specific Gravity	Apparent Kinematic Viscosity
41316	9/31/61	122.0	6.11	.000035	.016	1.10	.000016
41016	9/12/61	77.0	6.12	.000035	.016	1.10	.000016
41116	9/12/61	86.0	6.12	.000029	.019	1.10	.000014
41005	8/ 8/61	77.0	6.27	.000033	.016	1.11	.000015
41105	8/ 8/61	77.0	6.29	.000032	.016	1.11	.000015
41205	8/ 8/61	77.0	6.29	.000032	.016	1.11	.000015
41022	9/15/61	77.0	3.12	.000025	.010	1.05	.000012
41122	9/15/61	86.0	3.12	.000023	.010	1.05	.000011
41222	9/15/61	104.0	3.12	.000019	.010	1.05	.000009
41322	9/15/61	122.0	3.26	.000017	.010	1.06	.000008
41422	9/15/61	145.4	3.26	.000012	.013	1.06	.000006
41015	9/12/61	77.0	3.94	.000026	.011	1.07	.000013
41115	9/12/61	86.0	3.94	.000024	.012	1.07	.000012
41215	9/12/61	104.0	3.94	.000020	.012	1.07	.000010
41004	8/ 7/61	77.0	3.96	.000031	.014	1.07	.000015
41104	8/ 7/61	77.0	3.96	.000029	.018	1.07	.000014
41204	8/ 7/61	77.0	3.96	.000030	.010	1.07	.000015
41317	9/13/61	122.0	8.09	.000045	.025	1.14	.000020
41417	9/13/61	145.4	8.09	.000042	.026	1.14	.000019
41017	9/13/61	77.0	8.09	.000063	.021	1.14	.000028
41117	9/13/61	86.0	8.09	.000057	.023	1.14	.000026
41217	9/13/61	104.0	8.09	.000051	.024	1.14	.000023
41008	8/ 8/61	77.0	10.36	.000075	.028	1.18	.000033
41108	8/ 8/61	77.0	10.36	.000076	.027	1.18	.000033
41018	9/13/61	77.0	10.22	.000077	.037	1.17	.000034
41118	9/13/61	86.0	10.22	.000071	.038	1.17	.000031
41218	9/13/61	104.0	10.22	.000062	.039	1.17	.000027
41318	9/13/61	122.0	10.30	.000058	.041	1.18	.000025
41418	9/13/61	145.4	10.30	.000050	.046	1.18	.000022
41009	8/ 9/61	77.0	11.73	.000079	.046	1.20	.000034
41109	8/ 9/61	77.0	11.73	.000087	.040	1.20	.000037
41209	8/ 9/61	77.0	11.73	.000086	.040	1.20	.000037
41309	8/ 9/61	77.0	11.73	.000085	.039	1.20	.000036
41011	8/10/61	77.0	15.22	.000114	.086	1.26	.000047
41111	8/10/61	77.0	15.22	.000110	.080	1.26	.000045
41012	8/11/61	77.0	16.14	.000127	.102	1.28	.000052
41112	8/11/61	77.0	16.14	.000127	.100	1.28	.000051
41010	8/ 9/61	77.0	17.12	.000133	.155	1.29	.000053
41110	8/ 9/61	77.0	17.12	.000140	.146	1.29	.000056

TABLE F - 26

RHEOLOGICAL DATA

SERIES 44,000 - FINES-WATER SLURRIES

Run Number	Date	Temperature, °F.	Concentration Fines, % by Volume	Coefficient of Rigidity Lb. Sec./Ft.^{2}	Yield Stress Lb./Ft.^{2}	Specific Gravity	Apparent Kinematic Viscosity
44017	8/29/61	77.0	9.28	.000071	.027	1.16	.000032
44117	8/19/61	77.0	9.28	.000068	.028	1.16	.000030
44011	8/26/61	77.0	9.33	.000071	.027	1.16	.000032
44111	8/16/61	77.0	9.33	.000069	.027	1.16	.000031
44014	8/26/61	77.0	9.33	.000065	.027	1.16	.000029
44114	8/26/61	77.0	9.33	.000065	.027	1.16	.000029
44016	8/28/61	77.0	9.33	.000070	.028	1.16	.000031
44116	8/28/61	77.0	9.33	.000069	.028	1.16	.000031
44018	8/29/61	77.0	9.33	.000069	.026	1.16	.000031
44118	8/29/61	77.0	9.33	.000071	.025	1.16	.000031
44023	8/29/61	77.0	9.33	.000072	.027	1.16	.000032
44123	8/29/61	77.0	9.33	.000072	.026	.116	.000032
44024	8/30/61	77.0	9.33	.000068	.031	1.16	.000030
44124	8/30/61	77.0	9.33	.000070	.029	1.16	.000031
44027	8/30/61	77.0	9.33	.000068	.029	1.16	.000030
44127	8/30/61	77.0	9.33	.000069	.027	1.16	.000031
44031	8/31/61	77.0	9.33	.000068	.030	1.16	.000030
44131	8/31/61	77.0	9.33	.000070	.029	1.16	.000031
44021	8/29/61	77.0	9.38	.000069	.027	1.16	.000031
44121	8/29/61	77.0	9.38	.000069	.027	1.16	.000031
44006	8/25/61	77.0	9.43	.000071	.028	1.16	.000031
44106	8/25/61	77.0	9.43	.000071	.027	1.16	.000032
44108	8/25/61	77.0	9.43	.000072	.027	1.16	.000032
44108	8/25/61	77.0	9.43	.000070	.027	1.16	.000031
44012	8/26/61	77.0	9.43	.000072	.028	1.16	.000032
44112	8/26/61	77.0	9.43	.000073	.026	1.16	.000033
44015	8/26/61	77.0	9.43	.000072	.027	1.16	.000032
44115	8/26/61	77.0	9.43	.000073	.027	1.16	.000032
44026	8/30/61	77.0	9.43	.000067	.030	1.16	.000030
44126	8/30/61	77.0	9.43	.000070	.029	1.16	.000031
44028	8/30/61	77.0	9.43	.000067	.029	1.16	.000030
44128	8/30/61	77.0	9.43	.000070	.027	1.16	.000031
44020	8/29/61	77.0	9.48	.000073	.026	1.16	.000032
44120	8/29/61	77.0	9.48	.000071	.026	1.16	.000032
44033	8/31/61	77.0	12.77	.000056	.018	1.22	.000024